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MECHANICAL FASTENING OF TITANIUM AND ITS ALLOYS

By D. L. Cheever, R. E. Keith, R. E. Monroe, and D. C. Martin

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ABSTRACT

This report covers the state of the art on mechanically fastening titanium and its alloys. The report emphasizes the differences that are encountered in designing, forming, machining, and assembling titanium joints as compared with the standard practices for more common alloys.

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PREFACE

This report is one of a series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract DA-01-021-AMC-11651(Z), in the general field of materials fabrication.

This report is primarily intended for the use of design and manufacturing engineers who have previous experience in mechanically fastening steel and aluminum. When the mechanical fastening of joints composed of titanium and its alloys is demonstrably different from the fastening of common materials, the differences are reported. Where no known differences exist between the procedures for mechanically fastening titanium alloys and the procedures for the more common alloys, the report does not repeat at length the information or procedures that are readily available or widely known.

An extensive literature search was conducted within Battelle that included the Main Library, the Defense Metals Information Center, and Fasteners Research Council Technical Abstracts, with an examination of references extending back to 1958. In some cases, pertinent references with earlier dates were used to supplement more recent information. Outside Battelle, the Defense Documentation Center and the Redstone Scientific Information Center were searched. In addition to the literature search, a review was made of trade information available from titanium-fastener manufacturers. Additional data were obtained from contacts with fastener manufacturers and from manufacturing organizations that were mechanically fastening materials for aerospace applications.

The authors wish to acknowledge the help of Vernon W. Ellzey and Albert G. Imgram of Battelle, Project Technical Coordinators and Walter Veazie, Battelle Information Specialist.

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MECHANICAL FASTENING OF TITANIUM AND ITS ALLOYS

SUMMARY

Successful assembly of titanium products joined by mechanical fasteners requires an understanding of the principles of designing, forming, machining, and assembling joints composed of titanium and its alloys. The considerations and procedures for mechanically fastening titanium and its alloys are emphasized where they contrast with the fastening of the more common steel, aluminum, and copper alloys. Fabrication of titanium products is generally more costly because of the necessary cleaning procedures required to prevent the formation or to avoid the presence of brittle surface layers. The machining of titanium joints requires different procedures than are normally used with the more common alloys.

Other than the consideration of several general characteristics of titanium, the selection of specific fastener designs from the stock available differs very little from the selection of fasteners for joints composed of other alloys.

Difficulties that can occur during the design and fabrication of titanium products using mechanically fastened joints can be minimized by following the recommendations of this report.

INTRODUCTION

As the technology of forming, machining, and assembling titanium and its alloys has developed, mechanically fastened titanium joints have been used more widely in industry.* The basic methods of joining metals are: mechanical fastening, adhesive bonding, welding, brazing, soldering, and solid-state bonding. Mechanically fastened joints have several advantages over joints made by other methods.

*Two words that are quite similar, yet have special meanings within this report, are defined to avoid confusion. The words are "fastener" and "fastening". A fastener is a specific mechanical device that mechanically joins two or more parts to form a joint. The fastening of joints is a process only and usually requires the use of mechanical fasteners. The end result is a mechanically fastened joint.

For example, a joint that has been mechanically fastened can be rapidly inspected, visually and nondestructively, for any overall defects in the joint. Some mechanical fasteners can be disassembled and reassembled. Mechanically fastened joints also have disadvantages when compared with joints made by other techniques. The need for gaskets or sealants to produce leak-tight joints and the weight and bulk of mechanically fastened joints have limited their use in some critical applications.

Mechanical fasteners are available with a large number of sizes, shapes, and functions. The best source of information about fasteners is the fastener manufacturer. However, there are fastener reference manuals published by Machine Design (Ref. 1) which contain excellent references to the general fastener field. Other compilations of data about specific fasteners also are available.

Joints in titanium structures have been made with a variety of types of fasteners made from many materials. The type of fastener used is usually determined by the expected loads and the type of loading the joint will meet in service. The material from which the fastener is made is also determined by many factors. If light weight is essential, titanium or aluminum fasteners may be used. If high strength is needed, the fasteners may be made from high-strength steels such as H11 or SAE 4340. If high temperatures are to be encountered in service, the fasteners may be made from A286 or another high-temperature alloy. If ease of forming is needed, the fastener may be made from Monel. The service environment also influences fastener selection.

This report will deal specifically with design and production considerations that are encountered during the fastening of titanium and its alloys with mechanical fasteners. For additional information on other joining methods, see the Redstone Scientific Information Center reports on adhesive bonding of titanium by Keith, Monroe, and Martin (Ref. 2) and on welding, brazing, and soldering of titanium by Vagi, Monroe, and Martin. (Ref. 3).

The mechanical fastening of titanium and its alloys has been confined primarily to the airframe, aerospace propulsion, and the chemical industries. The airframe and aerospace propulsion industries have utilized titanium to obtain the high strength-to-weight ratio that titanium and titanium alloys maintain up to moderately high temperatures. The chemical industry has used titanium in applications where high corrosion resistance, particularly to chlorides, was mandatory.

A large number of mechanically fastened joints in titanium have been made in airframes. In some cases, the titanium structure has been put together with non-titanium fasteners. In other cases, titanium fasteners have been used to assemble non-titanium structures. Examples of each of these uses are described below.

Figure 1 shows a wing-box fuel-containment cell built by Lockheed-California under the FAA-ASD supersonic-transport development program (Ref. 4). The wing box shown was assembled from titanium sheet and stringers. Titanium fasteners were not used in this assembly. All of the structural fasteners used in the wing box were H11 steel, HT 240 screws heat treated to 260 ksi. Silverplated A286 nuts were used with the screws, a practice now restricted. The restriction most probably results from the accelerated salt corrosion of titanium and titanium alloys in the presence of silver. Titanium-alloy fasteners are presently being evaluated for use in similar structures (Ref. 5).

FIGURE 1. LOCKHEED FAA-ASD WING-BOX FUEL-CONTAINMENT CELL AND TYPICAL TRUSS SPAR (REF. 4)

Titanium structure assembled with non-titanium fasteners.

Photograph courtesy of Lockheed-California Company.

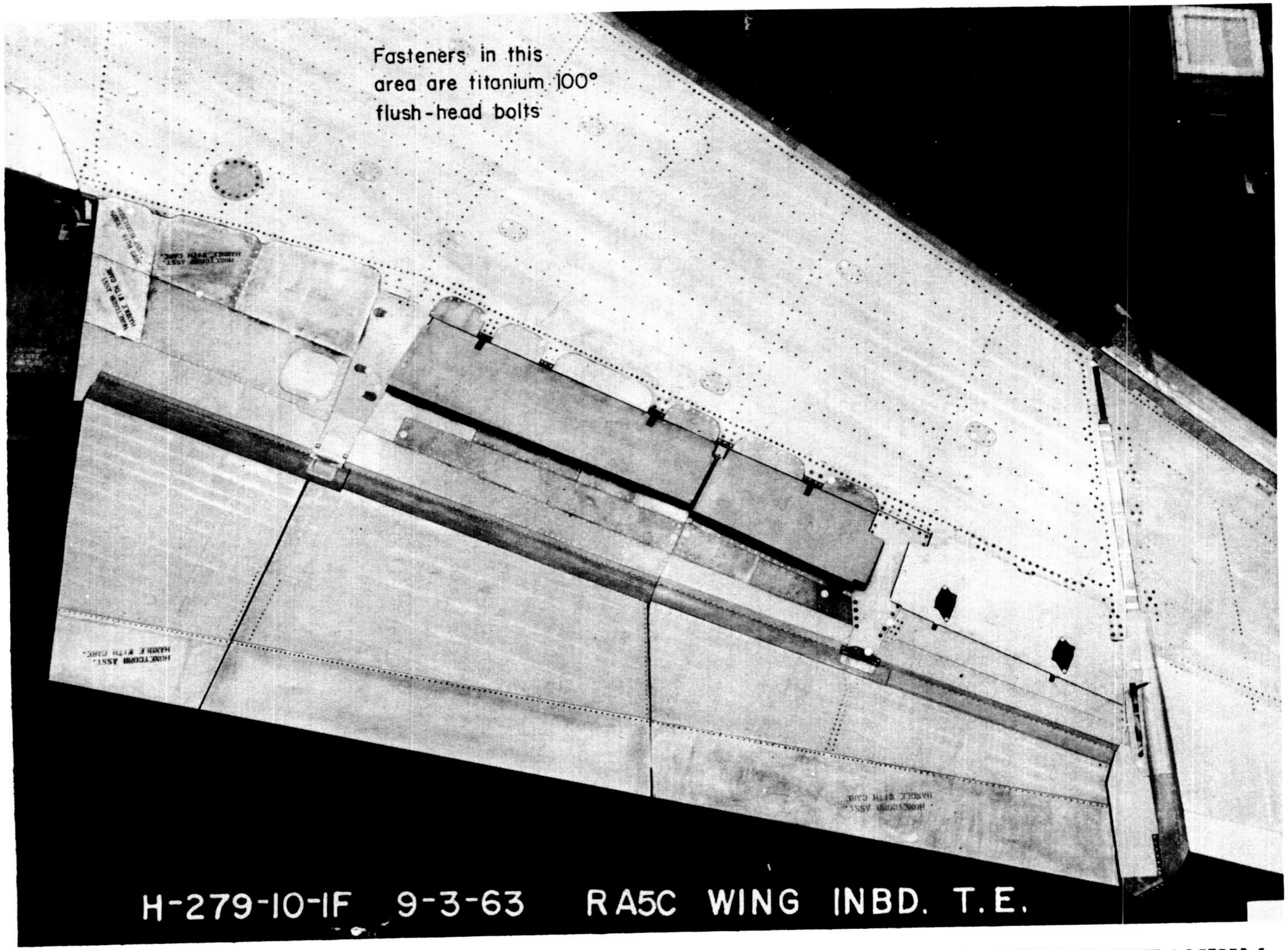


FIGURE 2. INBOARD TRAILING EDGE OF TA5C AIRCRAFT SHOWING TITANIUM FASTENERS IN ALUMINUM STRUCTURE

Photograph courtesy of Columbus Division, North American Aviation.

Titanium fasteners were used by North American Aviation in the fabrication of the inboard trailing edge of the RA5C aircraft in the integral fuel-tank area. A photograph of this structure is shown in Figure 2. The 100-degree flush-head Ti-4Al-4Mn bolts were used to join aluminum sheet to the aluminum structure (Refs. 6, 7). Titanium fasteners were used because of their high strength-to-weight ratio.

This report describes the considerations that should be used in the design and fabrication of mechanically fastened joints of titanium and its alloys, particularly when the considerations differ from those used for fastening more common engineering materials. Where the processes necessary to mechanically fasten titanium and its alloys have not been reported to differ from widely known and widely used processes, less detail is presented. For these reasons, specific data of the type currently available in handbooks detailing items such as edge spacing have not been included. With the increasing use of titanium in industry, the applications of mechanically fastened titanium joints will increase and more information regarding the fastening processes should become available.

TITANIUM ALLOYS

Titanium alloys are classified on the basis of metallurgical structure into three basic groups: alpha, alpha-beta, and beta alloys. The single-phase alpha alloys are not heat treatable and are usually alloys with good weldability. The notable alloying metal in present commercial alpha alloys is aluminum. Alpha-beta titanium two-phase alloys are heat treatable and do not always have good weldability. Beta alloys contain roughly 10 per cent or more manganese, molybdenum, chromium, or vanadium. Beta alloys do not respond as readily to heat treatment as do the alpha-beta alloys. Table I classifies several of the more common titanium alloys by alloy type.

TABLE I. PREDOMINANT METALLURGICAL STRUCTURE OF COMMON TITANIUM ALLOYS

Alpha	Alpha-Beta	Beta
Commercially pure titanium	Ti-1Al-8V-5Fe	Ti-13V-11Cr-3Al
Ti-5Al-2.5Sn	Ti-6Al-4V	
Ti-7Al-2Cb-1Ta	Ti-4Al-4Mn	
Ti-7Al-12Zr	Ti-6Al-2Sn-6V	
Ti-8Al-1Mo-1V	Ti-7Al-4Mo	

Titanium has been successfully used in applications requiring good corrosion resistance, high strength-to-weight ratio, a modulus of elasticity between that of aluminum and steel, low magnetic properties, and high strength at temperatures up to 800 F. The tensile strength-to-weight ratio of the heat-treated alpha-beta alloys is somewhat greater than that of high-strength aluminum alloys and steels. This favorable ratio accounts for much of the use of titanium in airframes.

The density of titanium is about 0. 16 lb/cu in. as compared with 0. 10 for aluminum and 0. 28 for iron. The modulus of elasticity of titanium ranges from 15 to 18 million psi, which is somewhat more than the modulus of aluminum and about half that of steel. Alloying and processing can increase the hardness of commercially pure titanium from 160 Brinell hardness to as high as 450. The brittleness of titanium increases with the presence of interstitial alloying elements such as oxygen, hydrogen, nitrogen, and carbon. Titanium readily reacts with oxygen at temperatures above 1000 F to form a brittle oxide layer.

The ultimate tensile strength ranges from 35 ksi for commercially pure titanium to 210 ksi for highly alloyed titanium. Table II shows typical mechanical properties of a number of commercial titanium materials. The endurance limit of titanium is the same as that of most other metals, about 50 per cent of the ultimate tensile strength. Heat treatment of titanium can result in good impact resistance along with high tensile strength and good ductility.

TABLE II. TYPICAL MECHANICAL PROPERTIES OF COMMERCIAL TITANIUM-ALLOY FASTENERS (REF. 8)

Alloy	Temperature, F	Ultimate Strength, ksi	0.2 Per Cent Yield Strength, ksi	Shear Strength, ksi
Ti-7Al-12Zr	-423	260	240	140
Ti-7Al-12Zr	RT	160	150	105
Ti-7Al-12Zr	760	120	90	70
Ti-6Al-4V	-423	310	290	155
Ti-6Al-4V	RT	170	165	110
Ti-6Al-4V	400	145	125	82
185 titanium	-423	290	--	110
185 titanium	RT	225	220	135
185 titanium	300	180	180	110

Depending upon the alloy, titanium generally retains usable strength properties up to 800 F as shown in Figure 3. Specific alloys may be used above this upper limit. The creep resistance of titanium is highest from 400 to 600 F and is lower above and below this range. The decreasing strength and modulus of elasticity experienced by titanium at high temperatures leads to a loss of rigidity.

The coefficient of sliding friction of titanium is high. Sliding surfaces of titanium tend to "cold weld", or gall, unless a suitable surface treatment has been applied. The thermal conductivity of titanium is very low for a metal, less than one-fifth that of steel and one-tenth that of aluminum. The low thermal conductivity is one of the primary factors to be considered when titanium is machined. The corrosion resistance of titanium alloys is high in oxidizing environments and low in reducing environments. Stress-corrosion cracking of titanium occurs in the presence of chloride ions and also in other environments.

JOINT DESIGN

Mechanically fastened joints are made in a variety of ways. Mechanical fasteners range from shrink-fitted parts to turbine-blade "fir trees", keys, spring retainers, screws, rivets, and bolts. A majority of the design and production considerations necessary for mechanically fastening titanium and its alloys with bolts or rivets are applicable to joints using the less common, specialized fasteners.

Most of the experience in mechanical fastening has been acquired with materials other than titanium. However, most of the techniques applicable to fastening of other materials are also applicable to titanium. The advantages of mechanically fastening titanium joints when compared with the other methods of joining are:

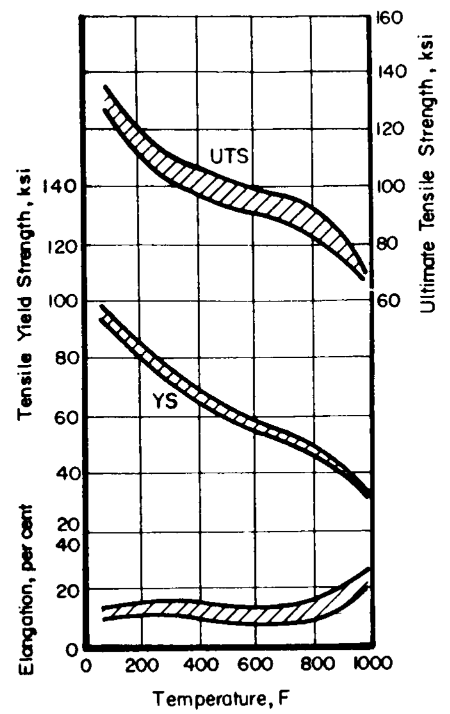
(1) Well-established fabricating and designing methods

(2) Provision for nondestructive disassembly

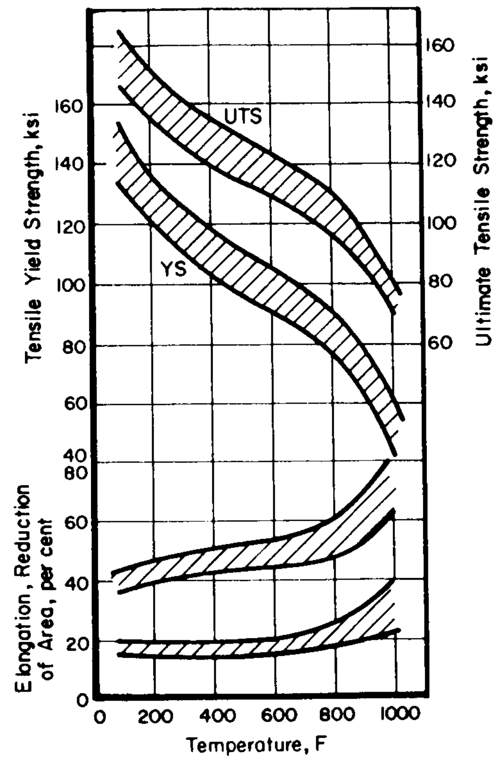
(3) Overall soundness of mechanically fastened joint is readily inspected visually

(4) Capable of joining dissimilar metals

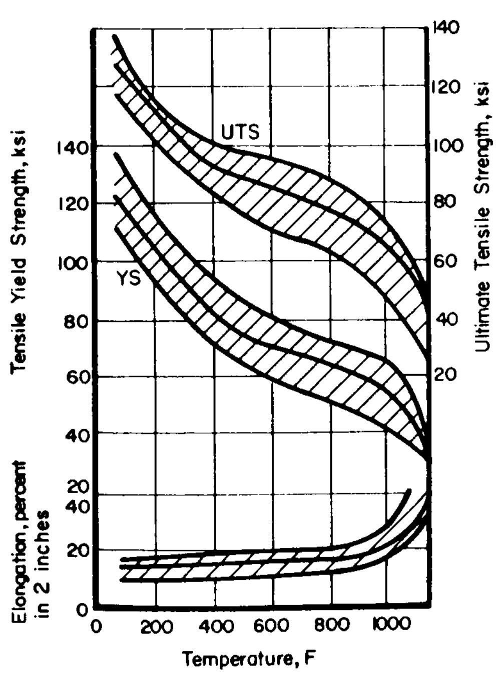
(5) Less thermal damaging of structure



a. Ti-6Al-4V
Annealed, 0.063-in. sheet (48 tests).



b. Ti-4Al-4Mn
Annealed, bar.



c. Ti-5Al-2.5 Sn
Annealed, sheet.

FIGURE 3. VARIATION OF MECHANICAL PROPERTIES WITH TEMPERATURE FOR THREE TITANIUM ALLOYS (REF. 9)

(6) Less expensive equipment requirements

(7) Less surface cleaning or preparation

(8) Less elaborate jigging or tooling for assembly.

Methods and Design. The mechanical fastening of joints is a widely used joining method. The design principles of joints for mechanical fasteners have been well established.

Accessibility. The use of mechanically fastened joints is necessary in designs where access panels are required or where disassembly is necessary.

Inspection. The overall soundness of a mechanically fastened joint can be inspected readily by simple visual examination.

Dissimilar Metals. Dissimilar metals can be joined successfully by mechanical fastening as long as the service environment does not allow galvanic corrosion to occur or if the dissimilar metals are electrically isolated by insulators.

Thermal Damage. The only thermal effects that are encountered in the fabrication of mechanically fastened joints are the heats of machining and forming or the heat given off by hot-driven rivets. Heating of the structure during mechanical fastening is usually much less than the heat required during the other joining processes.

Equipment. Equipment associated with mechanical fasteners is widely manufactured, easily obtained, and of inherent simplicity. Very little regulation of the fastening process is necessary to produce good joints.

Cleaning. Special cleaning and handling procedures can often be avoided or minimized by the use of mechanically fastened titanium joints. The most restrictive requirement is that the edge and holes should be burr free. The use or presence of chlorinated solutions is to be avoided when stress-corrosion cracking might occur.

Assembly. Mechanical fasteners can readily draw joints together as a part is mechanically fastened. Rigid tooling and an exact fit-up are therefore less important during fabrication of mechanically fastened joints than in welding or adhesive bonding. The generally low ductility of high-strength titanium, when compared with other metals, does require that the machining and forming be sufficient to allow the parts to be drawn easily together during fabrication.

The cost of mechanically fastening titanium as compared with other methods of joining depends partially upon the existing equipment and the experience of a particular plant. The configurations of the joints and the number of items to be produced also must enter into cost comparisons.

Some limitations of mechanically fastened joints are:

(1) Stress concentration
(2) Residual stresses
(3) Electrical conductivity
(4) Weight
(5) Gaskets required for seals
(6) Thickness limitations
(7) Irregular outside surfaces
(8) Galling tendency.

Stress Concentration. The load across a mechanically fastened joint is concentrated at each mechanical fastener. The removal of metal for holes or fastener bearing surfaces also reduces the joint strength.

Residual Stresses. Residual stresses can be created in the permanent deformation of fasteners or of the joint under the fasteners. In addition, machining may leave high, localized residual stresses. Operations such as dimpling or joggling create high residual stresses unless the parts are subsequently heat treated after assembly.

Electrical Conductivity. Mechanical fasteners provide metal-to-metal contact both between the plates being joined and between the fastener and the plates. In corrosive environments, contact between dissimilar-metal compositions will cause the less-noble metal to be attacked. Generally, titanium is the more noble of any metal combination. The use of the same alloy throughout the joint will not eliminate galvanic corrosion if differences exist in the metal history, e. g. , a cold-worked rivet in contact with a heat-treated plate. Recent studies have shown that zinc-chromate primer enhanced corrosion resistance of a mechanically fastened joint composed of aluminum plate and a titanium fastener (Ref. 8). Proprietary coatings are widely available in epoxy paints, plastic coatings, or ceramic coatings.

Weight. Not only must a weight consideration be made for the mechanical fasteners, but many joints also require extra weight for the laps and for the additional pieces required when mechanically fastening a joint.

Seals. Mechanically fastened joints are not inherently leak-proof. Generally, either an organic coating or an elastomer are used as gaskets. For proper sealing, the surface condition and fit-up of mechanical joints become critical. Elastomer seals (notably silicone rubber) are available with moderate service life at moderately elevated temperatures. Manufacturers should be contacted for the most complete information on the newest seals. The upper temperature limits of the better sealing materials are just below the temperature range where use of titanium becomes most attractive.

The use of gaskets or materials with a lower modulus of elasticity than the two structural parts of the joint decreases the fatigue life of the joint. The stiffness of the joint is decreased with the use of a gasket. Thus the usefulness of preloaded fasteners with gasketed joints diminishes as the more easily deformed gasket allows greater deformation of the joint and fastener. The deformation of the joint also causes larger stress variations in the fastener. Subsequent early failure by fatigue can result. The use of gaskets with thin plate requires that the bolt preload be carefully selected. Underloading a bolt used with a gasketed joint can allow leakage. However, overloading can cause the gasket to buckle between the fasteners and allow leakage, too.

Thickness Limitations. Thin materials are joined by mechanical fasteners with difficulty. The bearing stress exerted by the fastener on the sheet can cause a tearing type of failure.

Irregular Outside Surface. Unless countersunk or dimpled holes are used with countersunk fasteners, the surface of a mechanically fastened joint will not be smooth and flush. In critical fastenings and assemblies, the ripples and waviness between the fasteners can be completely unacceptable even if the fasteners are recessed.

Galling. The high coefficient of sliding friction, the low thermal conductivity, and the high reactivity of titanium combine to cause severe galling or "cold welding" of the titanium surfaces that slide across one another. Titanium surfaces should never be used in sliding applications unless a lubricant is present. Sulfides of tungsten or molybdenum have been successfully applied as lubricants to reduce galling. These lubricants are unsuitable for use with vacuum environments where outgassing and evaporation occur or with liquid oxygen. Several proprietary lubricants, one of which is compatible with liquid oxygen, are listed by Glackin and Gowen (Ref. 8). The galling of threaded titanium fasteners with titanium nuts has resulted in the general use of steel and aluminum nuts. Even in applications where weight is critical, the cost and limited availability of titanium nuts may make the use of steel nuts preferable.

GENERAL DESIGN OF MECHANICALLY FASTENED JOINTS

Standard practices for the design of bolted and riveted joints are readily available in numerous handbooks and codes. Manufacturers' catalogs list numerous commercially available fasteners that are made of titanium or are suitable for use with titanium and its alloys. A detailed handbook by Laughner and Hargan (Ref. 10) tabulates the dimensions of commonly used fasteners.

Types of Loading. Mechanically fastened joints can be classified in many ways. One useful classification is based on whether the fastener is loaded in tension or shear. Another useful classification is based on whether the joint is permanent or made with removable fasteners. Permanent joints are usually made with rivets although threaded fasteners may be used. Separable joints are made with threaded fasteners. If high-strength fasteners are required, threaded fasteners are used.

Well-designed joints have all joint members in balance. Failure may occur in the joint members or in the fastener. Consequently, fastener sizes and spacing should be chosen with consideration for the thickness and properties of the materials being joined and for the expected loadings. Some basic equations that can be used in choosing fastener and joint designs are given below (Ref. 1).

Fastener shear load:

$$P_s = S_s A_n \quad ,$$

Fastener load in tension:

$$P_t = S_t A \quad ,$$

Root diameter area:

$$A_r = 0.7854 \left(D - \frac{1.3}{N}\right)^2 ,$$

Tensile stress area of threaded section:

$$A_s = 0.7854 \left(D - \frac{0.9743}{N}\right)^2 ,$$

Bearing failure load:

$$P_b = S_b A_b$$

or

$$P_b = S_b t D ,$$

Plate tensile strength:

$$P_u = S_u (W - mD) t ,$$

where

A = Root diameter area of threaded section, sq in.

A_b = Area in bearing, sq in.

A_r = Effective cross-sectional area, sq in.

A_s = Tensile stress area of a threaded area, sq in.

D = Nominal diameter of fastener, in.

m = Number of rivets in transverse row

n = Number of shear planes

N = Number of shear threads per inch

P_b = Ultimate bearing strength of joint, lb

P_s = Fastener shear load, lb.

P_t = Fastener load in tension, lb

P_u = Tensile failure load, lb

S_b = Ultimate bearing strength of plate, psi

S_s = Fastener shear stress, psi

S_t = Fastener stress in tension, psi

S_u = Ultimate tensile strength of plate, psi

W = Width of plate, in.

Rivets, in general, are used most often in joints which are loaded in pure shear. Tensile forces tend to pry the rivet away from the parts being joined to cause serious loosening with consequent fatigue of the rivet. Threaded fasteners are used in both shear and tension joints.

Titanium fasteners should be considered for shear loading whenever minimum weight is a design consideration. Recent comparative tests of fasteners made of two different titanium alloys given an indication of possible design properties. The shear strength, of No. 10-1/4-inch bolts of Ti-7Al-12Zr ranged from 130 ksi at -400 F to 50 ksi at 800 F (Ref. 8). Similar bolts of Ti-6Al-4V maintained shear strengths ranging from 155 ksi at -400 F to 65 ksi at 400 F (Ref. 8).

Joint Configurations. Figure 4 illustrates a number of designs for joints using flat sheet. These joint designs are the basic elements of the more complicated joints that are used in actual structures. The joints shown are used primarily in sheet metal or plate structures and can be used with either rivets or threaded fasteners. Figure 5 illustrates six common modes of failure in the basic mechanically fastened joint. Failure by bending, pure shear, or tensile rupture of a joint can be avoided by designing and selecting the joint elements to be of sufficient strength, size, and rigidity. Crushing is avoided by proper selection of the fastener diameter or of the joint thickness. Failure in the margin is generally avoided by the standard practice of spacing fasteners one and one-half times their diameter from the edge (some handbooks recommend two diameters distance). To reduce sensitivity to impact, sharp transitions and changes of section should be avoided in designs for use under impact loading (Ref. 11).

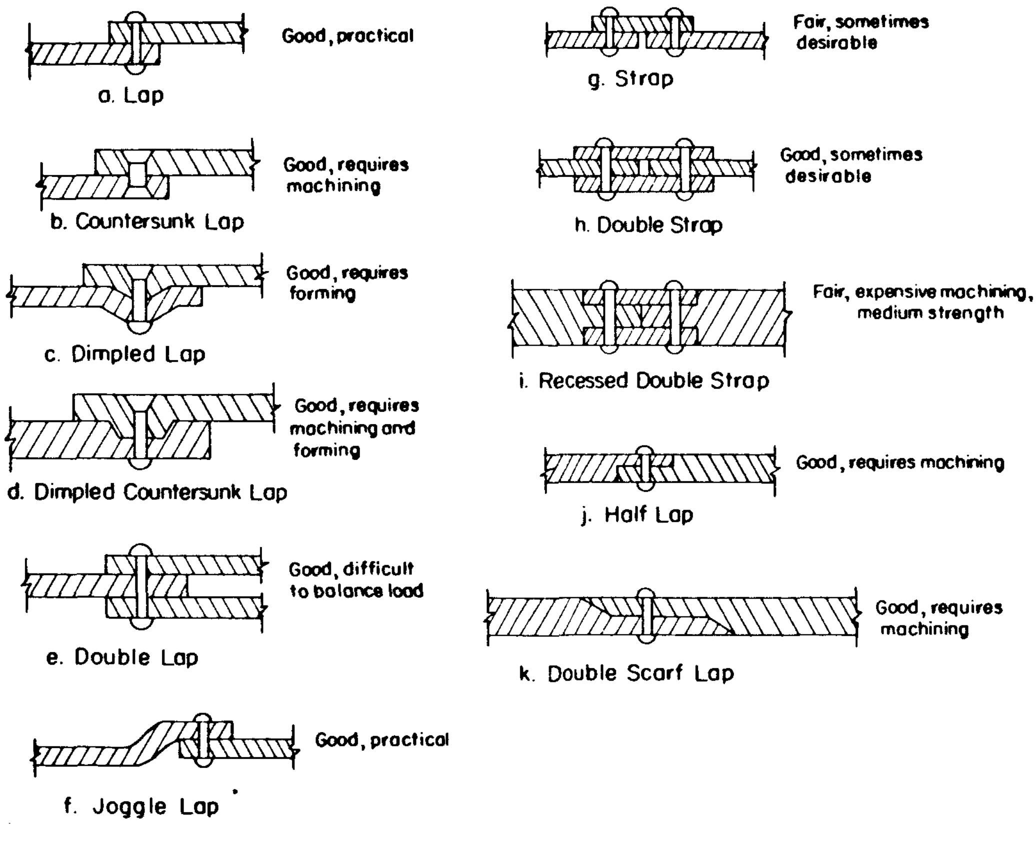


FIGURE 4. BASIC DESIGNS FOR JOINTS IN FLAT SHEET

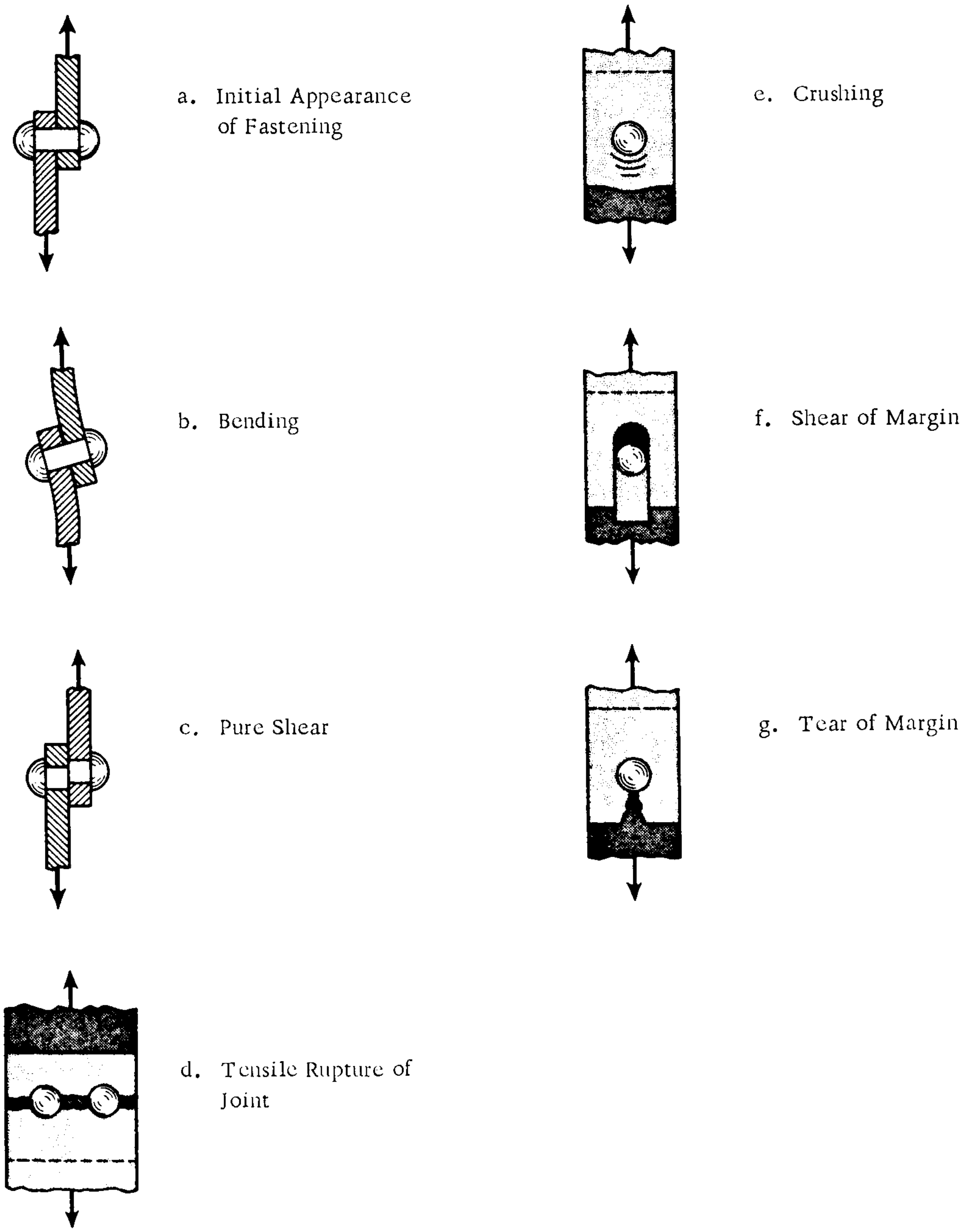


FIGURE 5. TYPES OF FAILURE IN SHEAR-LOADED SHANK-TYPE JOINTS (REF. 12)

Tension Fasteners. Tension fasteners are best used where cyclic tensile stresses act upon a fastener. Tension fasteners are generally threaded fasteners. Proper selection of the fastener, design of the joint, and preload of the fastener will eliminate failure due to loosening and increase the fatigue life of the joint. A fastener is most highly stressed during the tightening of the fastener because of the application of torque to overcome friction and to tighten the fastener. Removal of the tightening torque leaves only the preload. Although torquing of a bolt beyond the yield point of the bolt causes permanent deformation, the residual tensile stress remains the same as in a bolt torqued to just below the yield point. The practice of torquing above the yield point allows consistent achievement of the highest preload-force capability of the fastener but there are two limitations. The first limitation is that the bolt cannot be reused. The second limitation is that imprecise control of the tightening torque may cause failure in materials such as titanium, where the ultimate tensile strength is not much higher than the yield strength. Use of bolts with a high preload can cause permanent deformation of the bolt and a subsequent decrease in preload and joint life if allowance is not made for thermal expansion forces or other external load conditions.

Shear Fasteners. A preloaded joint can resist shear action when the clamping force across the joint is so great that the friction between the fastener and the plate prevents relative movement between the two. Ideally, the clearance between the fastener and the hole is of no importance when the clamping force is sufficient to resist shear. The high coefficient of surface friction for titanium surfaces allows very effective clamping with smaller bolt loads than are used with other materials. The cold-welding tendency for sliding titanium surfaces is a desirable property in clamping applications and makes attractive the use of titanium fasteners with titanium joints when a permanent joint is desired.

High-Temperature Design. The mechanical properties of titanium, like those of any metal, change with temperature. Figure 3 shows the variation of properties of some titanium alloys with temperature. The mechanical properties of alpha-beta and beta alloys, which are usually heat treated to varying degrees of hardness, are dependent upon the service temperatures and service times because of the unstable character of the metallurgical components that make up these alloys. The room-temperature strengths of the alpha-beta and beta alloys achieved by the combination of processing and heat treatment are high. A large percentage decrease in the tensile strength and the fatigue life of a heat-treated titanium-alloy fastener occurs

TABLE III. EFFECT OF TIME AND TEMPERATURE ON PROPERTIES OF AIR-COOLED NAS674 TITANIUM FASTENERS AT ELEVATED TEMPERATURES (REF. 13)

Titanium Alloy	Part Number	Before Soaking: Average Ultimate Tensile Strength, ksi	Before Soaking: Average Shear, ksi	Before Soaking: Fatigue,[a] 10^3 cycles	Soaking: Temp, F	Soaking: Time, hr	After Soaking: Average Ultimate Tensile Strength, ksi	After Soaking: Average Shear, ksi	After Soaking: Fatigue 10^3 cycles	Percentage Decrease: Ultimate Tensile Strength,	Percentage Decrease: Shear
Ti-4Al-4Mn	NAS674-17	192.4	112.1	62- 102N	700	10	129.6	109.6	10- 32TF[b] 3NF[c]	32.5	2.2
Ti-6Al-4V	NAS674-10	198.1	107.0	60- 92NF	550	10	196.1	106.0	2TF 3NF[c]	1.0	.93
Ti-6Al-4V	NAS674-13	197.5	110.1	60- 104NF	550	10	101.2	109.8	2TF	3.2	.27
Ti-6Al-4V	NAS674-10	196.5	106.5	60- 122NF	700	10	179.2	102.9	19- 31TF	8.8	3.4
Ti-7Al-4Mo	NAS674-24	199.3	108.3	63- 117NF	700	10	161.3	107.1	35- 58TF	19.1	1.1
Ti-4Al-4Mo-4V	NAS674-11	208.0	116.4	67-1078NF	600	100	101.1	--	4- 17TF	51.4	--
Ti-8Al-8Zr-1(Cb+Ta)	NAS674- 9	162.0	96.9	133- 182NF	700	10	161.5	95.1	131-134NF	0.3	1.8
Ti-8Al-8Zr-1(Cb+Ta)	NAS674-10	170.3	100.2	131- 182NF	700	10	169.0	99.0	152-218NF	0.8	1.2
Ti-8Al-1Mo-1V	NAS674-10	178.4	104.3	92- 277NF	700	10	172.5	106.4	45-254NF	3.3	--
Ti-8Al-1Mo-1V	NAS674-10	178.4	104.3	92- 277NF	700	100	170.4	102.8	4TF[c] 1NF	4.5	--
Ti-1Al-8V-5Fe	NAS675-10	212.2	119.5	10- 55T-H[d]	700	10	107.7	117.7	1- 3TF	49.0	1.5
Ti-6Al-6V-2.5Sn	NAS674-10	217.2	119.3	49-1148TF	700	10	155.7	122.5	7- 18TF	28.0	2.6

(a) NF - no failure.
(b) TF - thread failure.
(c) Actual number of bolts sampled.
(d) T-H - thread and head failures.

after exposure to high temperatures. Table III shows the effect of temperature and time on the properties of a number of heat-treatable alloys.

In contrast, fasteners of alpha or alpha-beta alloys with a dominant alpha phase show little or no decrease in the ultimate tensile strength or the fatigue life after prolonged exposure. These alloys do not depend on heat treatment for strengthening. Selection of mechanical fasteners for high-temperature service should be based on strength values obtained at the design temperature after exposure for the design life.

The coefficient of thermal expansion for titanium is lower than that for most steels, stainless steels, and nickel alloys. Thermal expansion data for a number of titanium alloys and other structural materials are given in Figure 6. Mechanically fastened joints between titanium and other metals intended for high-temperature service must be designed to allow for loosening or tightening of the fastener as temperature changes occur. In most cases, the selection of a higher fastener preload and the selection of the joint materials will eliminate any thermal loosening problems. Tightening is not a problem unless the combination of the thermal stress with the preload and design load exceeds the yield point of the fastener, causing permanent deformation and loosening on subsequent cooling. High-temperature applications often must consider the decrease in preload that can occur due to relaxation of the bolt.

Low-Temperature Design. Many of the same factors considered in high-temperature design are equally important in considering low-temperature designs. Although, the properties of some titanium alloys are satisfactory at very low (cryogenic) temperatures, this is not the case for all alloys. A current NASA-sponsored study of fasteners for space applications (Ref. 14) has shown that the Ti-8Al-1Mo-1V alloy is not satisfactory for use at cryogenic temperatures because of unpredictable behavior. Conversely, the Ti-5Al-2.5Sn (ELI) alloy was found satisfactory.

Differences in the coefficient of expansion as shown in Figure 6 must be considered in low-temperature design. These differences indicate that it would be difficult to keep titanium tension fasteners tight in aluminum structures cooled to very low temperatures.

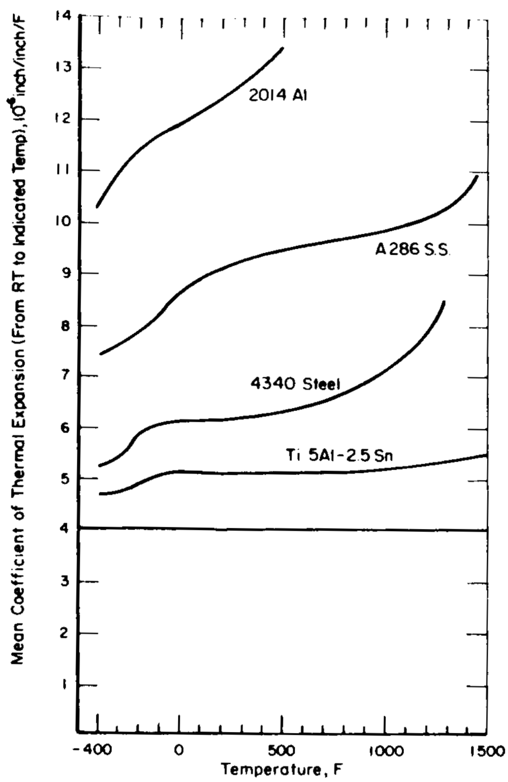


FIGURE 6. COMPARISON OF MEAN COEFFICIENT OF THERMAL EXPANSION OF TITANIUM TO OTHER MATERIALS (REF. 15,19)

The use of titanium, in any form, in a liquid oxygen (LOX) environment should be avoided. Titanium is very sensitive to catastrophic failure in liquid oxygen.

CORROSION

Although titanium, like stainless steels, is a highly corrosion-resistant material, it also can corrode in certain environments. In addition, the noble characteristics of titanium as compared with steel, aluminum, magnesium, and cadmium can cause rapid attack of these materials when they are in contact with titanium. The most common mistake made when designing equipment for use in corrosive conditions is to assume that the reported corrosion resistance of a metal at one temperature is indicative of the corrosion resistance of the metal at a higher temperature. A good discussion of corrosion and corrosion protection for titanium is contained in Titanium Metallurgical Laboratory Report Number 57 (Ref. 15).

The corrosion resistance of titanium results from the rapid formation of an oxide film on the surface when titanium is exposed to oxidizing atmospheres such as air. In service environments, the formation and tight adherence of a protective oxide film is dependent upon environment, the film and metal compositions, and crystal structures. In laboratory tests, titanium has been shown to corrode at a decreasing rate in a two-metal corrosion cell regardless of whether titanium is the anode or cathode (Ref. 15). Care must be taken in extrapolating laboratory test results to actual situations, since the aeration and the velocity of the fluid environment, the presence of inhibiting or accelerating reactants, and slight variations of the alloy composition can cause widely different corrosion rates. At high temperatures, where the oxide film is more porous and can be penetrated by active ions, titanium can be severely attacked by solutions that do not attack titanium at room temperature. The stress corrosion of titanium illustrates the effect of temperature upon corrosion. Titanium is sensitive to stress-corrosion cracking in the presence of chlorides at high temperatures. Boyd and Fink concluded that for 500 F and below, the hot-salt stress-corrosion cracking of Ti-8Al-1Mo-1V is not a serious problem. Above 550 F, stress-corrosion cracking can be a definite possibility (Ref. 17). The presence of silver or gold accelerates the failure of titanium at elevated temperatures in the presence of chlorides as shown in Figure 7.

Preliminary information from a number of sources at this time indicate that at room temperature the load-carrying capacity of titanium containing notches or cracks is reduced considerably in environments such as sea water.

When the corrosion resistance of a material is important, and where the available information is limited, tests of the proposed materials under simulated-service conditions avoid much uncertainty and possible losses. The actual corrosion rates may be found to be negligible and steps need not be taken to prevent corrosion.

Coating of the parts with a paint or plastic is often one way of reducing or avoiding decrease corrosion in mechanical joints. Zinc-chromate primers have been used on dissimilar-metal joints composed of titanium and aluminum with good results (Ref. 8). Cadmium-plated fasteners should not be used for high-temperature service. Cadmium melts at 610 F and will braze the fastener to the joint. Complete insulation of dissimilar metals also prevents galvanic corrosion.

Cracks and crevices should be avoided because they can retain corrosive liquids locally long after removal of the parts from the liquid. The holes and crevices inherent in mechanically fastened joints are possible restrictions to the use of mechanical fasteners in corrosive environments.

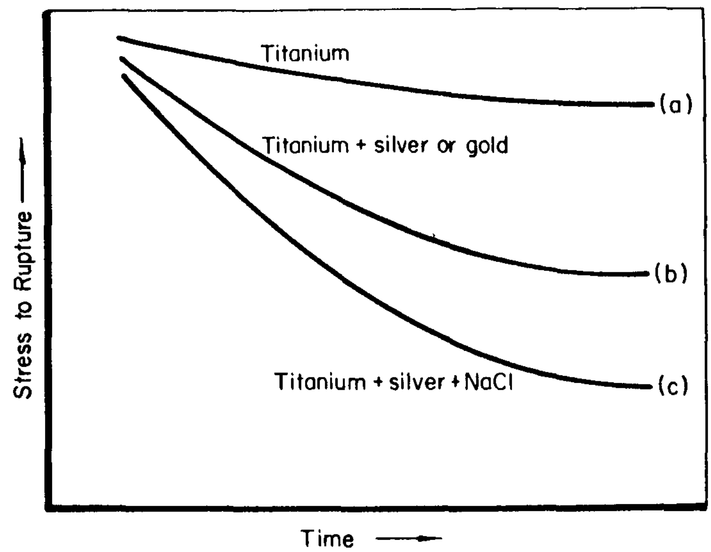


FIGURE 7. APPARENT EFFECT OF SILVER, GOLD, AND SODIUM CHLORIDE ON ELEVATED-TEMPERATURE STRESS-RUPTURE PROPERTIES OF TITANIUM

(a) Normal titanium stress-rupture curve.
(b) Titanium stress-rupture curve in presence of silver. Other braze alloys such as gold may cause similar behavior.
(c) Titanium stress-rupture curve in presence of silver and NaCl.

FASTENER SELECTION

Fasteners used for joining titanium and its alloys do not differ from those used for joining the more conventional materials. The specific information listed in recently published literature such as Reference 1 is helpful for surveying the fasteners available.

The selection of specific fasteners is dependent not only on the application but also on the cost, availability, necessary equipment required, and previous shop experience. Fastener manufacturers should be contacted for specific information and the details of the latest proprietary features. Almost any fastener design can be obtained in titanium if the customer is willing to pay the price and wait for the manufactur of the item. The following sections discuss considerations to be made when mechanically fastening titanium and its alloys with rivets and bolts.

The current production and availability of titanium rivets is limited. Commercially pure titanium rivets are available. During driving, the rivets work harden slightly at room temperature. Negative-clearance titanium rivets are difficult to install in titanium plate without lubrication of the rivet to prevent galling of the rivet in the hole.

Non-titanium rivets, particularly Monel, have been widely used in titanium joints. Table IV illustrates design allowables for such rivets. The characteristics and recommended practices for the use of these fasteners are readily supplied by most fastener or alloy manufacturers. The design of a titanium joint with non-titanium fasteners should consider both the effects of differential thermal expansion and galvanic corrosion. Aluminum and steel fasteners are subject to possible rapid attack when used with titanium in a corrosive environment. The use of copper-base, nickel-base, and stainless steel fasteners will reduce the possibility of galvanic corrosion between the fastener and the titanium joint.

The two basic bolt types are designed to be used with two different loads, shear and tension. Currently, threaded fasteners made from Ti-6Al-4V and Ti-4Al-4Mn are stocked by a number of suppliers. Additional alloys are being studied for use in future fastener designs.

In 1960, the Society of Automotive Engineers issued the Aeronautical Materials Specification AMS-7460, for heat-treated and roll-threaded bolts and screws. The specification is intended for bolts for use at temperatures up to 750 F. The specification details the acceptable dimensional tolerances, metallurgical properties, and specifies the flow-line appearance. The Appendix contains the specification as an example of the quality that can be obtained in high-precision titanium fasteners. Other specifications applying to titanium fasteners are listed in Table V.

TABLE IV. YIELD AND ULTIMATE STRENGTH OF SOLID 100-DEGREE-FLUSH-HEAD MONEL RIVETS IN MACHINE COUNTERSUNK TITANIUM ALLOYS

Sheet Material	Commercially Pure Titanium				AMS 4901 Alloy (Ti-8Mn)		
Rivet Diameter, in.	1/8	5/32	3/16	1/4	1/8	5/32	3/16
	Yield Strength, lb[a]						
Sheet Thickness, in. [b, c]							
0.020	180	--	--	--	180	--	--
0.025	229	276	--	--	229	276	--
0.032	297	364	429	--	297	364	429
0.036	335	410	484	--	335	410	484
0.040	376	460	546	709	736	460	546
0.045	422	518	619	800	422	518	619
0.050	472	582	688	897	472	582	688
0.063	598	736	877	1,150	598	736	877
0.071	648	835	993	1,300	648	835	993
0.080	648	945	1,130	1,481	648	945	1,130
0.090	--	995	1,268	1,680	--	995	1,268
0.100	--	995	1,420	1,860	--	995	1,420
0.125	--	--	1,430	2,340	--	--	1,430
0.160	--	--	1,430	2,590	--	--	1,430
0.190	--	--	--	2,590	--	--	--
0.250	--	--	--	2,590	--	--	--
	Ultimate Strength, lb[a]						
0.020	307[d]	--	--	--	307[d]		
0.025	386[d]	476[d]	--	--	386[d]	476[d]	
0.032	492[d]	613[d]	732[d]	--	426	596[d]	732[d]
0.036	516[d]	686[d]	820[d]	--	451	627[d]	820[d]
0.040	531	765[d]	917[d]	1,216[d]	477	658	874[d]
0.045	555	795[d]	1,033[d]	1,363[d]	506	698	918
0.050	573	818	1,118[d]	1,512[d]	536	734	965
0.063	626	885	1,198	1,910[d]	617	833	1,080
0.071	648	926	1,242	2,010[d]	648	894	1,152
0.080	648	971	1,302	2,090	648	961	1,243
0.090	--	995	1,360	2,185	--	995	1,330
0.100	--	995	1,421	2,260	--	995	1,421
0.125	--	--	1,430	2,460	--	--	1,430
0.160	--	--	1,430	2,590	--	--	1,430
0.190	--	--	--	2,590	--	--	--
0.250	--	--	--	2,590	--	--	--

(a) Higher allowables may be used if substantiated by test.
(b) Sheet gage is that of the countersunk sheet. Data are not applicable where the lower sheet is thinner than the upper sheet.
(c) In each strength column the sheet gage corresponding to the first strength value below the horizontal line in the column (—) represents the thinnest sheet gage of the top sheet in which the full depth of countersink can be made without entering the bottom sheet.
(d) For these values the yield load is less than two-thirds of the indicated ultimate load values.
Note: Values in this table are based on "good" manufacturing practice, any deviation from this will produce reduced values.

TABLE V. STANDARDS FOR TITANIUM-ALLOY FASTENERS

Fastener	Type	Specification
Bolts		
Hex Head, Close Tolerance	Short Thread	NAS 653-568(2) NAS 673-678(2) NAS 1266-1270(2)
100-Degree Flat Head, Close Tolerance	Short Thread	NAS 1083-1088(2) NAS 663-668(2)
Lock, Shear, 100-Degree Head	Pull Type Stump Type	NAS 2506-2512(2) NAS 2606-2612(2)
Lock, Tension, 100-Degree (AN509) Head	Pull Type Stump Type	NAS 2106-2110(2) NAS 2306-2310(2)
Lock, Tension, Protruding Head	Pull Type Stump Type	NAS 2006-2010(2) NAS 2206-2210(2)
Twelve Point	External Wrenching	NAS 1271-1280(2)
Bolts and Screws (Ti-6Al-4V) Heat Treated	Roll Threaded	AMS 7460A
Bolts and Screws (Ti-6Al-4V) Upset Headed, Heat Treated	Roll-Threaded	AMS-7461
Rivets	100-Degree Interference Fit	NAS 1906-1916(2)
	Flat Head, Interference Fit	NAS 1806-1816(2)
General		
Fasteners, Titanium and Titanium Base Alloys, Design and Usage Limitations		MS 33592

JOINT PREPARATION

Fabrication of mechanical joints involves many steps that occur long before the joint is ready for assembly. In processing titanium, the initial preparation is often important to the ultimate performance of the finished mechanical joint. Processing operations of particular importance are:

(1) Cleaning
(2) Forming
(3) Machining
(4) Inspection.

Each of these operations is discussed in some detail in the following sections. Particular emphasis is placed on factors related to successful fabrication, assembly, and service of mechanically fastened joints in titanium and titanium alloys.

CLEANING OF TITANIUM

The brittle oxide layer that forms on titanium in the presence of oxygen shortens the life of machine tools. The oxide layer can be removed by the cleaning methods discussed below.

The sensitivity of titanium to contaminants that are generally present on metal parts and that can be tolerated during the fabrication of steel and aluminum has been a major cause of titanium-fabrication problems. Neglect of rigorous cleaning standards has caused losses due to contamination of titanium parts that were many times the additional cost required to obtain satisfactorily contaminant-free surfaces. Haphazard cleaning operations can, at best, result in a product of widely varying quality. At worst, contamination can make it impossible to obtain satisfactory parts. A flow sheet showing a typical cleaning operation for titanium is shown in Figure 8.

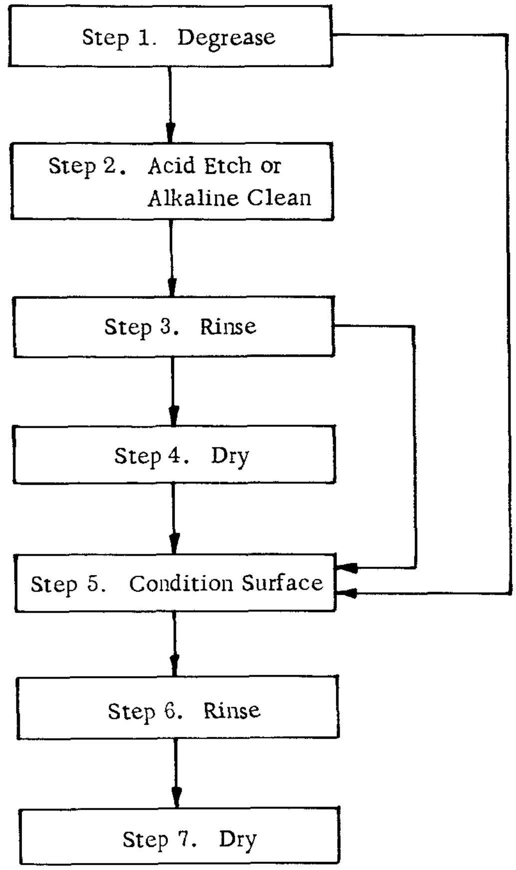


FIGURE 8. FLOW SHEET FOR TYPICAL CLEANING PROCEDURES OF TITANIUM

Cleaning Solutions. Oxide films or scale can be removed by a pickling or acid-etching treatment while organic materials are usually removed by an alkaline cleaning solution. Suggested formulas are given in Table VI (Ref. 19). In addition, many proprietary solutions are available for titanium-surface treatment. Care must be taken to follow the solution manufacturers' instructions. Where the size of a part exceeds the size of available treatment tanks, wiping may be necessary. The results obtained from wiping will be of higher quality if points where the surface is badly contaminated are pretreated by scrubbing or by mechanical abrasion. In some cases, the use of mechanical abrasive alone may be preferable. When abrasion is used, care must be taken to remove the abrasive residue.

TABLE VI. SUGGESTED CLEANING SOLUTIONS FOR USE WITH TITANIUM[a]

Removal of Light Scale and Tarnish
Bath Composition: 40 to 43% by weight NaOH Bath Temperature: 260 F Immersion Time: 5 to 30 minutes
or
Bath Composition: 50% NaOH and 10% $CuSO_4 \cdot 5H_2O$ by weight Bath Temperature: ~220 F Immersion Time: 10 to 20 minutes
Acid Pickling
Preparation: Degrease or alkaline clean and rinse with water Bath Composition: 15 to 40% HNO_3 and 1.0 to 2.0% HF by weight (maintain at least 15:1 ratio between HNO_3 and HF) Bath Temperature: 75 to 140 F Immersion Time: Unspecified Rinse: Clean water followed by 130 F clean-water spray

(a) These cleaning procedures are from Reference 2, which contains a complete listing of chemical cleaning baths used prior to adhesive bonding titanium and its alloys.

Different alloys of titanium will be attacked by acid and alkaline etches at varying rates. Alloys that contain lower percentages of alloying elements are more resistant, in general. Appreciable hydrogen pickup can occur during treatment in strong acidic etching solutions, particularly sulfuric acid. Hydrogen not only forms a brittle hydride on the titanium surface, it may embrittle the metal and cause porosity in welds in titanium alloys. It has been reported that a hydrogen pickup of 81 ppm by Ti-6Al-4V, (0.051-inch-thick sheet) can occur after 1 minute in hot, concentrated sulfuric acid (Ref. 20).

An extensive review of descaling and cleaning procedures for titanium, cite evidence that hydrogen pickup in titanium can be held to a minimum by using a pickling solution containing ten parts of nitric to one part of hydrofluoric acids by volume (Ref. 21). At this acid ratio, the metal-removal reaction is:

$$3Ti + 4HNO_3 + 12HF \rightarrow 3TiF_4 + 8H_2O + 4NO \ .$$

If the nitric-acid content is allowed to become depleted, however, the reaction changes to:

$$2Ti + 6HF \longrightarrow 2TiF_3 + 3H_2 \quad ,$$

with hydrogen solution in the metal taking place. The 10:1 acid ratio, which is commonly used as a rule of thumb, was established for Ti-8Mn alloy. Some evidence has been cited which indicates that Ti-6Al-4V, Ti-5Al-2.5Sn, and commercially pure titanium are relatively insensitive to the acid ratio, and that Ti-4Al-4Mn is more sensitive than Ti-8Mn.

Rinsing. Opinions differ as to whether water rinses should be hot or cold; tap, demineralized, or distilled water; immersion or spray; or whether the hot rinse should precede the cold. It has been recommended that the electrical conductance of water to be used for a spray rinse in adhesive-bonding applications be less than 10 micromhos, and that water for a tank rinse be less than 30 micromhos (Ref. 22). Water in many plants contains organic materials which may recontaminate the surface. Tap water also contains varying amounts of non-organic impurities, chlorine among them. To determine whether tap water in a given locality can be used for rinsing, tests should be made of the sensitivity of the application to the type of rinse water. Use of tap water rinsing is not generally recommended, however. Whatever the rinsing procedure used, the objective is the complete removal of the etching or cleaning solution, as indicated by neutrality of the effluent rinse water. Residual etching or cleaning solutions may cause corrosion of the joint.

TITANIUM FORMING

Currently, most titanium forming is carried out at elevated temperatures. The springback of titanium alloys formed at room temperature is usually high and unpredictable. This necessitates the use of high forming temperatures. Alloys that can be formed quite readily at room temperature are available. Material suppliers can provide forming recommendations for many specific applications. The Redstone Scientific Information Center report prepared by Gerds, Strohecker, Byrer, and Boulger (Ref. 22) on the deformation processing of titanium and its alloys contains detailed information regarding titanium forming.

Hot-Forming Equipment. Hot forming requires equipment capable of maintaining loads at elevated temperatures for at least one-half hour. Dies used for hot forming should be free of any contaminating agents. The parts to be hot formed should be free of oxide scale or other harmful surface materials. The pieces to be formed are heated in an inert atmosphere or with a protective coating to prevent contamination and subsequent cracking of the surface. After hot forming, a dye-penetrant test for cracks is advisable to avoid further operations on any defective parts (Ref. 4).

Dimpling. Dimpling is a forming process that is used with countersunk head fasteners to produce flush-surfaced joints. Dimpling is used primarily where the components of the joint are too thin to have the holes countersunk. Dimpled joints are made either with one sheet dimpled and the surface of the adjacent joint component countersunk or with multiple-dimpled components. Figure 4 illustrates both of these joints. Dimpling of titanium sheet is readily accomplished with the use of proper dimpling shape, dimpling rate, and dimpling temperature (Ref. 23). Sheets are dimpled in the condition in which they will be assembled. If heat treatment of the sheet occurs after dimpling, the resultant sheet distortion can cause misalignment of holes and dimples. Since dimpling requires a large amount of sheet ductility, most dimpling of titanium alloys is done at elevated temperatures. Ram-coin dimpling is used for most dimpling operations on titanium. Figure 9 illustrates the basic tooling used in ram-coin dimpling. Reference 23 contains recommended parameters for dimpling titanium alloys.

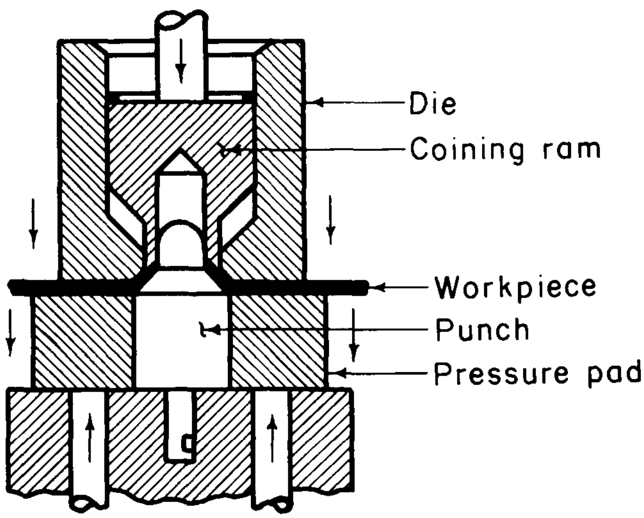


FIGURE 9. TOOLING FOR RAM-COIN DIMPLING (REF. 24)

The practical, optimum temperature limit for dimpling titanium alloys at elevated temperatures is 1200 F. This temperature is the highest temperature at which tool steels may be used as die materials (Ref. 23). The holes in the dimpled part should be free of burrs or roughness. Titanium alloys are dimpled with no lubricants. Conduction-heated, ram-coin dimpling equipment is used for sheet temperatures of up to 1000 F. Above this temperature, resistance heating is more commonly used. Figure 10 illustrates the five positions for triple-action ram-coin dimpling.

Joggling. Joggles are commonly used to join sheet together to obtain a flat surface on one side of the joint. A large number of joggling methods and types of joggling equipment are available. Hydraulic presses are frequently used for elevated-temperature joggling because the control of pressure and dwell time is quite simple (Ref. 23). Titanium and titanium alloys are usually joggled at elevated temperatures. Scratches and file marks should be avoided on pieces to be joggled. Lubricants are usually used during joggling. Tests (Ref. 25) have shown flake or powdered graphite are suitable for joggling lubricants at 850 F.

Springback in joggles made at room temperature or slightly above is as much as 50 per cent, depending upon the alloy. Generally, parts formed at these low temperatures must be hot sized to meet dimensional tolerances. Joggles produced in titanium at temperatures above 1100 F generally do not require further fabrication to tolerances (Ref. 23). Heat treatment of parts after joggling is not recommended because titanium will distort during the treatment. Table VII contains recommended joggling parameters for titanium and titanium alloys.

MACHINING OF TITANIUM JOINTS

Machining of titanium joints is necessary for the attachment of mechanical fasteners such as bolts and rivets. Holes have to be produced for through fastening; this can be done by punching or drilling.

Punching is not widely used to produce bolt or rivet holes in titanium parts. Most mechanical joints in titanium have been made in high-precision, high-quality applications. Not only does a punched hole create cracks and high residual stresses in the plate, but the resulting hole is generally low tolerance and requires deburring or reaming. The importance of hole tolerances and alignment is discussed later in the section on assembly.

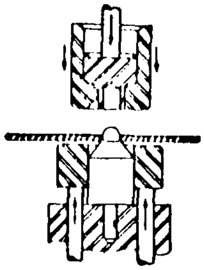
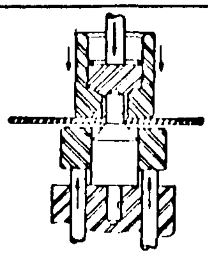
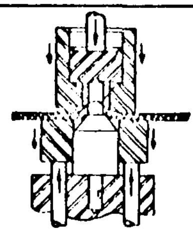
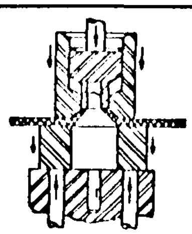
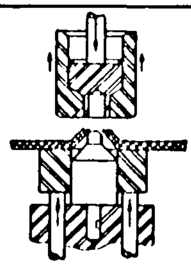
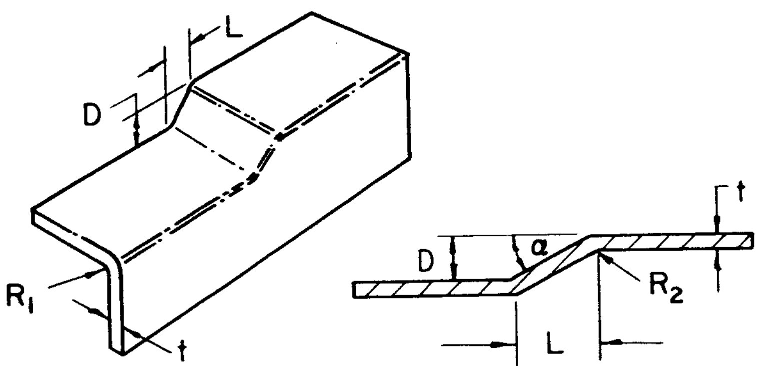
Position 1		**a. Approach** Sheet is positioned, with punch pilot in pilot hole and die assembly is coming down to contact position; loading force on coining ram is at preselected value
Position 2		**b. Preform** Die assembly has just contacted work, and timed heating stage is beginning; controlled preforming pressure is increasing to partially form dimple and to further accelerate heat transfer
Position 3		**c. Coining** Timed "Preform" stage has ended, and final coining stage begun; downward movement of die assembly is creating firm gripping action between die and pad faces in area around dimple, preventing outward flow of material as dimple is coined; coining ram controls hole stretch and balances internal strains, eliminating radial and internal shear cracks
Position 4		**d. End of Stroke** Dimple is now fully formed; the confining action of pad face, die face, and coining ram has forced material into exact conformation with tool geometry
Position 5		**e. Retraction** As die assembly retracts to starting position, load on pressure pad raises pressure pad to starting position and strips dimple from punch cone **f. Result** Minimum sheet stretch, minimum hole stretch, maximum definition, improved nesting

FIGURE 10. FIVE POSITIONS OF TRIPLE-ACTION RAM-COIN DIMPLING (REF. 26)

TABLE VII. LIMITING DESIGN PARAMETERS FOR JOGGLING TITANIUM ALLOYS[26, 27]

Alloy	Sheet Thickness, t, in.	Temp, F	Minimum Joggle Length, L, in.	Springback at Minimum Joggle Ratio, per cent
Ti-4Al-3Mo-1V	0.040	--	--	35
	0.063	Room	3.5 D	35
	0.090	"	4.25 D	~50
	0.063	600	3.0 D	--
	0.090	600	3.5 D	--
Ti-2.5Al-16V	0.040	Room	--	~45-50
	0.063	"	3.5 D	~45-50
	0.090	"	4.25 D	~60-65
Ti-13V-11Cr-3Al	0.025	"	1.5 D	13
	0.040	"	1.7 D	32
	0.063	"	1.7 D	40
	0.090	"	3.4 D	50
Ti-5Al-2.75Cr-1.25Fe	0.025	"	--	32.5
	0.040	"	--	46.8
	0.063	"	--	46.8



α = Joggle bend angle

D = Joggle depth

L = Joggle length or runout

t = Thickness of workpiece

R_1 = Radius on joggle block

R_2 = Radius of bend on leading edge of joggle block

Numerically controlled drilling has been used for a number of titanium joints to produce holes within the spacing and shape tolerances required.

A large amount of research has been conducted to determine the machining requirements for titanium. The most recent and comprehensive publication is the Redstone Scientific Information Center report by Olofson, Boulger, and Gurklis (Ref. 28).

Titanium-Machining Characteristics. The machining of titanium differs from the machining of copper, aluminum, and steel alloys for three interrelated reasons:

(1) The surface action of titanium is extremely abrasive with the usual tool materials because titanium tends to gall and smear on the tool.

(2) The low modulus of elasticity of titanium (compared with that of steel) and the low tool-chip angle requires the maintenance of high tool-bit pressures.

(3) The high tool-bit pressures and low tool-chip ratio in combination with the low thermal conductivity of titanium result in high local temperatures during machining.

The high temperatures mean that the cooling capacity of the cutting fluid used for machining titanium is generally more important than the lubricating qualities. Titanium chips tend to weld to a cutter as it leaves the work. When the cutter re-enters the work, the titanium chips welded to the tool are knocked off along with a part of the tool. Cutter life is shortened substantially if the design and use of cutting tools do not avoid this dulling action.

The machining of titanium is often compared with the machining of stainless steels. Such a comparison is more valid for estimating machining times than for describing the characteristics of titanium machining. The principal reason for the additional time required to machine titanium is the need to avoid high-removal speeds and heavy cuts.

Drilling. Holes for shank-type fasteners, such as bolts and rivets, are often drilled with the joint fitted up and clamped temporarily. Quality fastenings are generally drilled, disassembled, deburred and then permanently reassembled. Holes must be aligned perpendicular to the material surface. The reasons for this are discussed in the section on assembly.

The tool-bit condition, the drilling conditions, and the coolant-lubricant fluid are of great importance in drilling titanium. Unless proper machining conditions are used, the characteristically thin titanium chips tend to become wedged in the flutes of the drill. The drill condition is best checked by observing the tool-chip appearance. A sharp drill will form tightly curled chips. The appearance of a feathered-type of chip indicates a dulling point. The drill should be replaced when this occurs. Failure to replace a dulled drill can result in out-of-tolerance holes (Refs. 29, 30). When the drill has failed, irregular and discolored chips appear.

Five other important considerations for drilling titanium are (Ref. 28):

(1) Design blind holes to be as shallow as possible

(2) Use short drills with large flutes and special points

(3) Flush the tool machining surface with suitable cutting fluids

(4) Employ low speeds and positive feeds during drilling

(5) Supply solid support on the exit side of through-holes where burrs would otherwise form.

Table VIII contains suggested conditions for drilling titanium. Relief angles are of extreme importance in determining tool life. Small relief angles will increase the tendency of the drill to pick up titanium on the cutting edges. Excessively large relief angles greater than 12 degrees, are less desirable and can weaken the cutting edge (Refs. 29-32).

Dull drills should be entirely reconditioned to maintain the recommended drill geometry. Short drills are recommended to prevent the occurrence of out-of-round holes.

TABLE VIII. DRILLING TITANIUM ALLOYS WITH HIGH-SPEED STEEL DRILLS[a]

Titanium Alloy	Alloy Condition[b]	Tool Material[c]	Cutting Speed, fpm	Drill Diameter, inch	Feed, ipr, for Drill Shown[d]: C. P. Titanium and Titanium Alloys	Feed, ipr, for Drill Shown[d]: Ti-13V-11Cr-3Al
Commercially pure	An	M1, M2, M10	40 to 80	1/8	0.001-0.002	0.0005
Ti-8Al-1Mo-1V	An	Ditto	20 (40 for sheet)	1/4	0.002-0.005	0.001
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	An	"	40	1/2	0.003-0.006	0.0015
Ti-4Al-3Mo-1V	An	"	40 (25 for sheet)	3/4	0.004-0.007	0.0015
	STA	M33	20 for sheet			
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	An	M1, M2, M10	30 to 40	1	0.004-0.008	0.002
	STA	T15, M33	20 to 30			
Ti-7Al-4Mo Ti-6Al-6V-2Sn	An	M1, M2, M10	20	2	0.005-0.013	0.003
	STA	T15, M33	20			
Ti-13V-11Cr-3Al	An	M1, M2, M10	20 to 30	3	0.005-0.015	0.004
	STA	T15, M33	15 to 20			
Tool Geometry:	For general drilling operations, choose drill geometry x, y, or z depending on drill size (see Figure 10). For drilling sheet, use drill geometry, C, D, or B according to application (see Figure 11).					
Cutting Fluids Used	A valuable oil-water emulsion, or a sulfurized oil, the latter at lower speeds and for small drills (<1/4 inch). Chlorinated oils are also used provided oil residues are promptly removed by MEK. Holes in single sheets up to 2 times the drill diameter can be drilled dry.					

(a) From Ref 28.
(b) An = annealed; STA = solution treated and aged.
(c) AISI designations.
(d) Use the lower feeds for the stronger or aged alloys.

Care must be taken in the selection of the coolant-lubricant fluid for machining. Holes in single sheets with thicknesses under twice that of the drill diameter can usually be drilled dry (Refs. 30, 33). The lubricant action of cutting fluids is of importance in 1/4-inch-diameter holes and under. In holes with diameters larger than 1/4 inch, the coolant properties are of greater importance during drilling. Although heavily chlorinated or sulfochlorinated oils have been cited as fluids resulting in the best machining rates, a nonchlorinated fluid is preferable. The presence of chlorides on titanium during any heating operation should be avoided to remove the chance that stress-corrosion cracking will occur. Oil-water emulsions have been shown to be satisfactory coolants for drilling (Refs. 27, 28).

In no case should the tool bit be allowed to dwell in the work. The drill should be retracted as soon as the feed is stopped. Re-engaging the drill requires quick but careful replacement with the drill at the cutting speed and under positive feed. Chips should be removed regularly from the drill flutes by hand or by the coolant. Holes of more than one diameter depth require chip removal after every half diameter of advance. Up to No. 40 holes can be easily drilled by hand. Machine drilling is preferred when the hole is to be tapped (Ref. 32).

Reaming. Holes drilled in titanium should be reamed and the exit side deburred to bring the holes to Class 1 tolerances. As long as titanium does not adhere to the reamer to cause out-of-tolerance holes, reaming is accomplished easily. Spiral-fluted reamers with a 5 to 10-degree relief angle and a 0.010-inch-wide margin produce good hole finishes (Ref. 29) and reduce tool chatter. Carbide reaming tools have a very satisfactory tool life and are operated at speeds up to 200 fpm (Ref. 34). A sulfochlorinated oil appears to be the best cutting fluid (Ref. 29). However, it should be used with the realization that the use of this oil is objectionable wherever stress corrosion can later occur. Table IX shows suggested reaming conditions for titanium.

Tapping and Threading. The design of titanium fastenings should avoid whenever possible drilled and tapped holes. Tapping is regarded as the most difficult and troublesome titanium machining process (Ref. 35). However, the recent attention that has been directed to the problems of titanium tapping has led to a better understanding and may have improved tapping procedures. A recent report (Ref. 36) states that no significant difficulties were encountered during the tapping of 1/4- and 1/2-inch holes in a variety of situations.

TABLE IX. REAMING DATA FOR TITANIUM ALLOYS[a]

Titanium Alloy	Alloy Condition[b]	Tool Material[c] High-Speed Steel	Tool Material[c] Carbide	Cutting Speed, fpm: High-Speed Steel Initial	Cutting Speed, fpm: High-Speed Steel Final	Cutting Speed, fpm: Carbide Tipped Initial	Cutting Speed, fpm: Carbide Tipped Final	Reamer Diameter, inch	Feed, ipr, for Reamer Shown[d]: Commercially Pure, Annealed	Feed: Ti-13V-11Cr-3Al An	Feed: Ti-13V-11Cr-3Al STA	Feed: All Other Titanium Alloys[d]
Commercially pure	An	M2	C-2	40	70	65	250	1/8	0.003	0.002	0.002	0.002
Ti-8Al-1Mo-1V	An	M2	C-2	20	30	50	120	1/4	0.005	0.005	0.004	0.005
Ti-5Al-5Sn-5Zr Ti-5Al-2.5Sn Ti-7Al-2Cb-1Ta	An	M2	C-2	20	45	50	175	1/2	0.008	0.007	0.006	0.007
Ti-4Al-3Mo-1V	An	M2	C-2	20	45	50	175	1	0.011	0.009	0.008	0.009
Ti-7Al-12Zr Ti-6Al-4V Ti-8Mn	An STA	M2 M2	C-2 C-2	20 20	35 30	50 35	150 120	1-1/2	0.014	0.012	0.010	0.012
Ti-7Al-4Mo Ti-6Al-6V-2Sn	An STA	M2 M2	C-2 C-2	20 20	30 25	35 35	120 100	2	0.016	0.015	0.012	0.015
Ti-13V-11Cr-3Al	An STA	M2 M2	C-2 C-2	20 20	30 25	50 35	150 100					

Tool Angles, degrees

		Helix	Radial Rake	Relief	Clearance	Chamfer	Lead	Margin, inch
Tool Geometry	High-Speed Steel	10	3 to 5	5 to 10	10 to 15	45	--	0.010-0.015
	Carbide	7	6	5 to 10	10 to 15	45	2° x 3/16"	0.010-0.015

Cutting Fluids: Sulfurized, chlorinated or sulfochlorinated cutting oils. Clean off all oil residues with MEK.

(a) From Ref 28.
(b) An = annealed; STA = solution treated and aged.
(c) AISI designations for steels; CISC designations for carbides.
(d) Feeds are the same for both annealed and heat-treated alloys.

Holes to be tapped should be good quality with no wandering or tapering. If the drill has dulled in the hole and produced discolored chips, the surface of the hole has been contaminated (generally with oxygen) and is hard and brittle. Oxide scale created by any cause reduces the cutting life of tools (Ref. 4). A reduction in tap life not only increases machining costs but also increases the expensive possibility of taps breaking off inside holes.

The problems in tapping arise from titanium sticking to a dulling tap and causing the tap to form oversized holes and rough threads. The titanium smeared on the tool tends to gall against the edges of the hole and cause seizing of the tap in the hole. The additional torque necessary to overcome seizing, loads the tap and increases tapping stresses until the tool breaks (Ref. 36).

Tapping difficulties have been avoided by reducing the thread to 55 to 60 per cent of the full-thread requirements and then tapping the fewest number of threads allowable in each hole (Refs. 33-35). However, 75 per cent threads have been tapped successfully (Ref. 35). Designs should contain a minimum number of threads per hole and should avoid the more troublesome tapping of long through-holes and the tapping of blind holes.

Tapping of holes is best done automatically by a torque-sensitive machine that will reverse the tapping motion when a preset torque is exceeded. Machine tapping is successful only when use is made of a clutch that will prevent tap breakage. Machine tapping, unless done on a sensitive machine by a competent operator, can be difficult and troublesome (Ref. 30).

Since tapping is generally done when a piece is near final fabrication, extreme care should be taken during tapping to reduce the possibility of spoilage. Inspection of the taps for uneven wear or for near-microscopic smears of titanium on the tapping lands will help detect most approaching tap failures before they occur. Additional detailed information and references are given by Olofson, Boulger, and Gurklis (Ref. 28), and in Table X.

Modifications of conventional two-flute, spiral-point, plug-style H2-pitch-diameter taps have been used to the minor diameter. Full-land threads 0.015 inches wide should back up the cutting edges (Ref. 32). Sprial-point taps with interrupted threads and eccentric pitch-diameter relief have been successfully applied. Spiral-pointed taps generally cannot push chips forward in holes more than two diameters long (Ref. 36).

TABLE X. TAPPING DATA FOR TITANIUM AND ITS ALLOYS USING HIGH-SPEED STEEL TAPS[a]

AISI Type High-Speed Steel[b]	M1, M10 (nitrided)	
Tap Styles		
Tap Size	5/16-24 and smaller	3/8-16 and greater
Number of Flutes[c]	2 or 3	3 or 4
Tap Geometry		
Spiral Point Angle, degrees	10 to 17	
Spiral Angle, degrees	110	
Relief Angle, degrees	2 to 4	
Cutting-Rake Angle, degrees	6 to 10	
Chamfer Angle, degrees	8 to 10 or 3 to 4 threads	
Tapping Speeds, fpm		
Unalloyed Titanium	30 to 50	
Titanium Alloys[d]	10 to 30	
Ti-6Al-4V, Annealed	10 to 30	
Ti-6Al-4V, Aged	5 to 15	
Ti-8Al-1Mo-1V, Annealed	10 to 15	
Ti-13V-11Cr-3Al, Solution Treated	8 to 15	
Ti-13V-11Cr-3Al, Aged	5 to 7	
Tapping Lubricants	Lithopone paste (30% SAE 20 oil, 70% Lithopone); heavy sulfurized oil, sometimes fortified with molybdenum disulfide; barium hydroxide in water (5% by weight); highly chlorinated or sulfochlorinated oils followed by a thorough degreasing with MEK.	

(a) From Ref 23.

(b) M1 high speed steel is adequate for unalloyed titanium. M10 high-speed steel is best for titanium alloys. Nitrided taps generally give the best performance.

(c) Taps with two flutes normally do not give the support that the three or four-fluted taps provide; hence, use the latter two types for the larger sizes.

(d) Titanium alloys Ti-150A and Ti-140A at 30 fpm; Ti-4Al-4Mn at 20 fpm; annealed Ti-7Al-4Mo and Ti-6Al-6V-2Sn at 15 fpm; and aged Ti-7Al-4Mo and Ti-6Al-6V-2Sn at 10 fpm.

Lubrication. Ti-8Al-1Mo-1V has been tapped using a speed of 10 to 20 sfm with sulfurized oil in a flood application. When dry tapping was used (recommended only when use of lubricant restricted) the speed was dropped to 3 to 5 sfm (Ref. 34).

If the application of lithopone or zinc sulfide in oil (either is recommended) is difficult, a heavy sulfurized mineral oil gives good results (Ref. 29). Some use of molybdenum disulfide has been made during tapping. Taps should be precision ground and stress relieved. A chromium plating or heavy oxide helps prevent titanium smears that will shorten tap life.

Inspection. The use of dye-penetrant inspection at intermediate stages of fabrication is highly recommended to prevent the subsequent processing of a defective, cracked product. Preloaded bolts can be checked at random to determine whether the product has been properly assembled. Additional fatigue, bending, or tensile tests of the product may be required. Generally, there are few standardized tests methods for a complete assembly. The methods used vary for each manufacturer.

ASSEMBLY

The assembly techniques for designs utilizing titanium fastenings are similar to those used in aluminum or steel-alloy assembly except for the handling techniques. As has been previously mentioned, the maintenance of contaminant-free fabrication facilities is mandatory for critical applications. The assembly should be kept clean and free of harmful contaminants. The drilling of holes in place requires disassembly and deburring of the pieces before a fastener can be installed.

Titanium fasteners must be carefully aligned during assembly. Figure 11 illustrates the importance of proper alignment, especially for fasteners to be used at low temperatures. As shown in this figure, the strength of Ti-8Al-1Mo-1V bolts is drastically reduced in tests made with a 3-degree-angle block. Such a reduction is believed to indicate sensitivity to slight bending loads that might be imposed on the fasteners. Ti-5Al-2.5Sn (ELI) bolts also exhibited this sensitivity at -423 F but not at higher temperatures.

Alignment of a fastener can be no better than the alignment of the hole that it is inserted in. The need for particular care in hole-preparation operations (drilling, reaming) for titanium fasteners is apparent from a study of Figure 11.

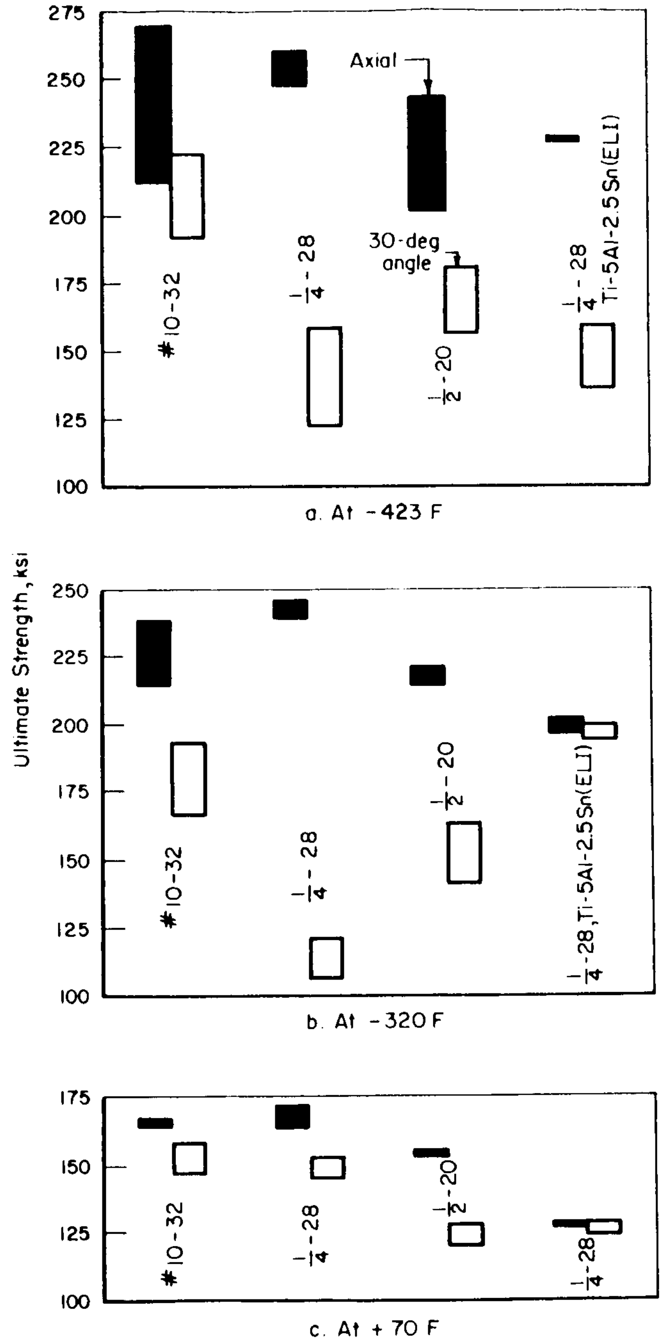


FIGURE 11. COMPARISON OF ULTIMATE STRENGTH WITH AXIAL AND 3-DEGREE-ANGLE-BLOCK LOADING (REF. 14)

Ti-8Al-1Mo-1V bolts with A-286 nuts.

The following sections discuss briefly methods of using several common fasteners.

Rivets. Riveting can be done in many ways, all of them useful for a number of different applications. Rivets are installed both cold and hot. However, in most industrial applications, cold riveting is used because of the speed, efficiency, and elimination of potential thermal damage to rivet and parts.

An old and still common method of setting rivets is with a rivet set and impact hammer. The important precautions are to use the proper size of rivet set, proper length of rivet, and to prevent battering of the parts being joined by set or back up.

Squeeze riveting is done by applying a steady force to both ends of the rivet. This type of riveting lends itself to more precise control than impact upsetting. Battering of the parts being joined is avoided. Squeezed rivets do not have an upset head. The rivet is bulged out to form a cylinder larger in diameter than the hole. This method of riveting is more tolerant of out-of-size holes and mismatching of holes than other methods of setting rivets.

If a head is required and impact riveting should be avoided, spin riveting can be used. Spin riveting produces a head on the rivet by rotating a tool against the rivet while the rivet is held still. Clamping pressure of the rivet is controlled by the upsetting parameters. This riveting method permits setting a rivet with no residual clamping pressure. This leaves the parts free to rotate around the rivet.

Bolts. An important factor influencing the strength of a bolted joint is the amount of pretensioning in the bolt. Consequently, it is necessary to produce the proper tension in the bolt during assembly. This is done by being sure that the proper torque is achieved during tightening. Bolts are tightened by:

(1) Turn-of-nut method. In this method, the nut is turned to a predetermined tightness (finger-tight) then given a specified amount of turn. The method is simple but not very accurate in producing a given pretension.

(2) Manual torque wrenching. A torque wrench has a dial that indicates the torque being applied. The nut is tightened to some preselected torque. Accurate but not fast.

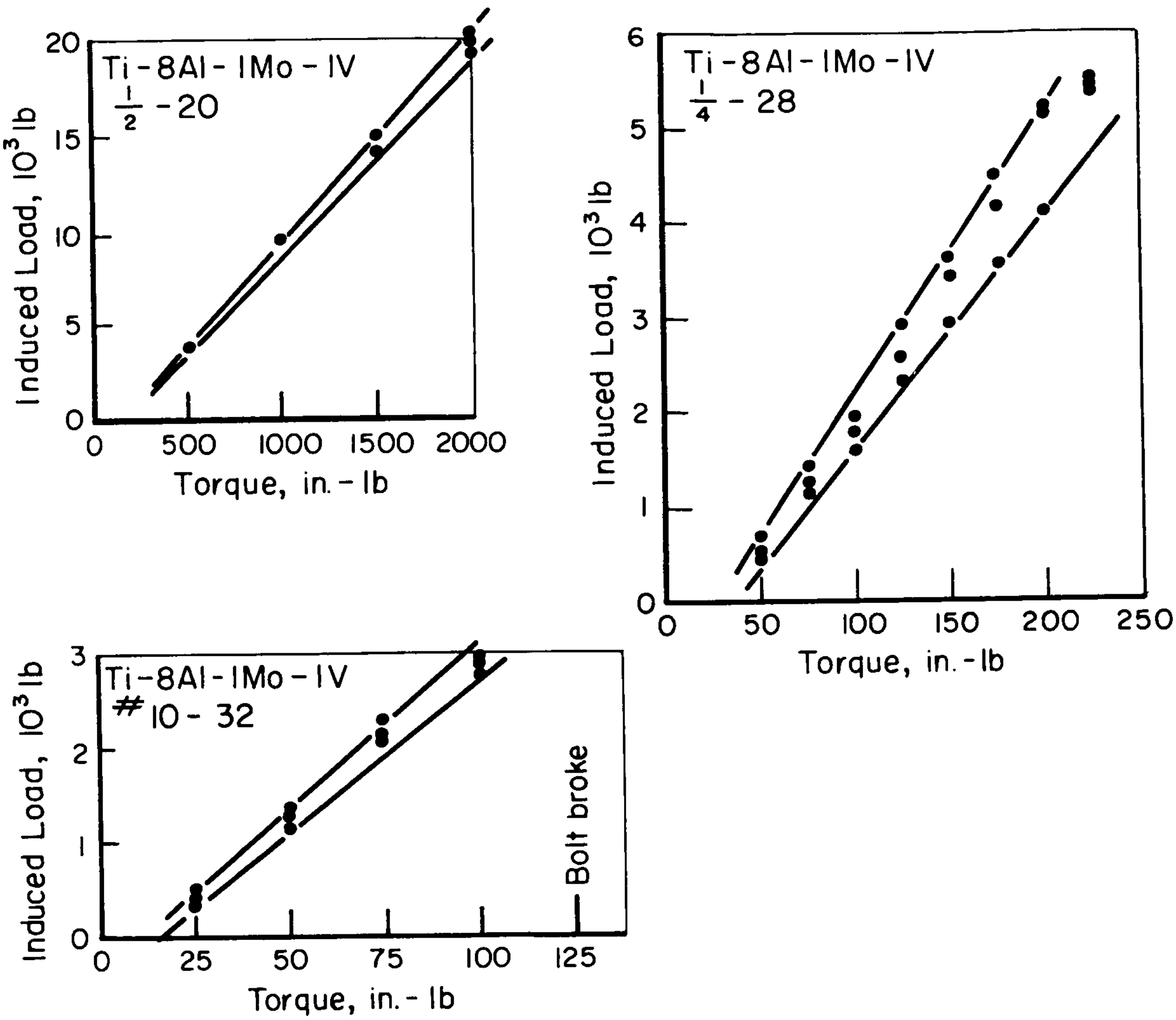


FIGURE 12. TORQUE VERSUS INDUCED LOAD FOR TITANIUM TENSION FASTENERS (REF. 14)

All data obtained from A-286 nuts. Bolt yield strength, 136 to 144 ksi; bolt ultimate strength, 154 to 171 ksi. Data from three consecutive tests, induced load generally higher on last test.

(3) Pneumatic impact wrench. Torque is controlled either by air pressure or by a cutoff. When air-pressure control is used the wrench stalls at the desired torque. The cutoff tool shuts off the air at the desired torque.

About 90 per cent of the torque applied during tightening is used to overcome friction. The balance produces tension in the bolt. With titanium fasteners, the torque required to overcome friction may be even higher. Figure 12 illustrates the induced load obtained in titanium bolts at several levels of torque. Data are plotted for three sizes of bolts. Actual torque values for critical applications should be arrived at by experiment.

CONCLUSIONS AND RECOMMENDATIONS

Preparation of this report has served to focus attention on a number of areas that need further development in the mechanical-fastening field and particularly in the fastening of titanium.

(1) Mechanical fastening, as a technology encompassing all aspects of the fastening operation from design through assembly, deserves better definition and recognition.

(2) Key words and other reference aids in Government reports should be used to show that fastener data are included.

(3) Additional data, as indicated, are needed in the areas listed below before the general production use of titanium in mechanically fastened joints.

a. Joints in titanium sheet or plate with nontitanium fasteners

(1) Stability of the fastening over the anticipated service temperature range

(2) Resistance of the fastening to corrosion in the anticipated service environment

b. Joints in nontitanium sheet or plate with titanium fasteners (or titanium bolts and nontitanium nuts)

   (1) Stability of the fastening over the anticipated service temperature range

   (2) Resistance of the fastening to corrosion in the anticipated service environment

   (3) Mechanical properties of the fasteners over the anticipated service temperature range

   (4) Torque-load data for fasteners

c. Any joints involving titanium

   (1) Design and mechanical property data for representative joints

   (2) Simulated service testing of prototype joints

APPENDIX

AERONAUTICAL MATERIAL SPECIFICATION AMS-7460*

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APPENDIX

AERONAUTICAL MATERIAL SPECIFICATION AMS-7460

BOLTS AND SCREWS, TITANIUM ALLOY
Heat Treated – Roll Threaded

1. ACKNOWLEDGMENT: A vendor shall mention this specification number in all quotations and when acknowledging purchase orders.

2. APPLICATION: High quality bolts and screws for use up to 750 F where a high strength lightweight fastener is required.

3. COMPOSITION: Shall conform to the latest issue of AMS 4928.

4. FABRICATION:

4.1 Blanks: Heads shall be formed by hot upsetting, cold upsetting, or machining.

4.1.1 The metal removed from the bearing surface of the head of upset-head blanks shall be as little as practicable to obtain a clean, smooth surface.

4.2 Heat Treatment: Headed and machined blanks shall, before finishing the shank and the bearing surface of the head and rolling the threads, be heat treated as follows:

4.2.1 Heating Equipment: Furnaces may be any type ensuring uniform temperature throughout the parts being treated and shall be equipped with, and operated by, automatic temperature controllers. The heating medium or atmosphere shall cause neither surface hardening other than that permitted in 5.5 nor embrittlement unless blanks are machined, after heat treatment, to remove surface hardening.

4.2.2 Solution Heat Treatment: Blanks shall be uniformly heated to 1550 F ± 25, held at heat for 1 hr, and quenched in water.

4.2.3 Precipitation Heat Treatment: Solution heat treated blanks shall be heated to 900 F ± 15, held at heat for 24 hr, and cooled in air.

4.3 Thread Rolling: Threads shall be formed on the finished, precipitation heat treated blanks by a single rolling.

5. TECHNICAL REQUIREMENTS:

5.1 Flow Lines: Flow lines of upset heads shall conform to the general arrangement shown in Figures 1A, 1B, or 1C. The intersection of the longitudinal axis of the part and the approximate transverse axis of the flow lines shall be not less than D/4 in. from the bearing surface for hexagonal, round, and square head bolts and screws and not less than D/7 in. from the bearing surface for 12 point head bolts and screws where D is the nominal diameter of the shank after heading.

5.2 Threads:

5.2.1 Flow lines at threads shall be continuous, shall follow the general thread contour, and shall be of maximum density at root of thread (see Figure 2).

5.2.2 Root defects such as notches, slivers, folds, roughness, or oxide scale are not permitted (see Figure 3).

5.2.3 Multiple laps on the sides of threads are not permissible regardless of location. Single laps on the sides of threads that extend toward the root are not permissible (see Figures 4 and 5).

5.2.4 A single lap is permissible along the side of the thread below the pitch diameter on the non-pressure side provided the lap does not originate closer than 20% of the basic thread height from the root and extends toward the crest and generally parallel to the side (see Figure 6). A single lap is permissible along the side of the thread above the pitch diameter on either the pressure or non-pressure side (one lap per thread) provided it extends toward the crest and generally parallel to the side (see Figure 7). Basic thread height is defined as being equivalent to 0.650 times the pitch (see Table I).

5.2.5 Crest craters, crest laps, or a crest lap in combination with a crest crater are permissible, provided the imperfection does not extend deeper than 20% of the basic thread height (see Table I) as measured from the thread crest when the thread major diameter is at minimum size (see Figure 8). The major diameter of the thread shall be measured prior to sectioning. As the major diameter of the thread approaches maximum size, values for crest crater or crest lap imperfections listed in Table I may be increased by 1/2 the difference between the minimum major diameter and the actual major diameter as measured on the part.

5.2.6 Slight deviations from thread contour are permissible at the crest of the thread within the major diameter limits as shown in Figure 9 and at the incomplete thread at each end of the threaded section.

5.2.7 Parts having holes for locking devices are permitted to have slight ovalization of the hole and the countersink and slight flattening of the crest of the thread at the countersink, provided the diameter of the hole is within specified chamfer, tolerances.

5.2.8 Parts shall have a minimum thread run-out of one thread and a maximum of two threads. The run-out shall fair onto the shank eliminating any abrupt change in cross sectional area. Bottom and sides of threads contained in run-out shall be filleted, smooth, and devoid of abrupt tool stop marks.

5.2.9 All thread elements shall be within specified limits starting at a length 2 times the pitch from the end, including chamfer, and extending for the specified full thread length.

5.3 Straightness, Concentricity, and Squareness: For purposes of these inspections, shank and threads shall be included but shall be considered as separate elements of the bolt.

5.3.1 Straightness of Shank and Threads: Shank and threads shall be straight within the limits specified on the drawing for the total length (L) of the bolt under the head (see Figure 10). Visibly abrupt changes in diameter or shape of the shank and threads which might cause stress concentrations are not permissible.

5.3.2 Concentricity of Thread Pitch Diameter: The concentricity of thread pitch diameter in relation to shank diameter shall be within the limits specified on the drawing for a distance of not less than 1.5 times the nominal bolt diameter away from the last full thread along the shank (see Figure 11). For bolts having a shank length less than 1.5 times the nominal bolt diameter, the concentricity of the shank diameter over its full length in relation to the thread pitch diameter shall be within the limits specified on the drawing.

5.3.3 Concentricity of Head: The concentricity of the head in relation to the shank diameter shall be within the limits specified on the drawing for a distance of not less than 1.5 times the nominal bolt diameter away from the washer face along the shank (see Figure 12). For bolts threaded to the head and for bolts having shank length less than 1.5 times the nominal bolt diameter, concentricity of head shall be measured in relation to thread pitch diameter in lieu of shank diameter.

5.3.4 Squareness of Washer Face: The squareness of the washer face with the shank diameter shall be within the limits specified on the drawing for a distance of not less than 1.5 times the nominal bolt diameter away from the washer face along the shank (see Figure 12). For bolts threaded to the head and for bolts having a shank length less than 1.5 times the nominal bolt diameter, squareness of washer face shall be measured in relation to thread pitch diameter in lieu of shank diameter.

5.4 Hardness: Shall be uniform and within the range of Rockwell C 36 - 42 or equivalent but hardness of the threaded portion may be higher as a result of the thread rolling.

5.5 Surface Hardening: Parts shall have no surface hardening except as produced during rolling of threads. Determinations of surface hardening may be made by microscopic method or by a sensitive hardness testing instrument.

5.6 Room Temperature Notched Stress-Rupture Test: Parts shall be capable of meeting the following requirement:

5.6.1 A part, maintained at room temperature while an axial stress of 170,000 psi is applied continuously, shall not rupture in less than 5 hours. The initial stress may be less than 170,000 psi and increased to 170,000 psi in increments of 10,000 psi at intervals of not less than 5 hours. The diameter of the area on which stress is based shall be taken as the maximum minor (nominal minor) diameter of the thread or the shank diameter, whichever is smaller.

5.6.1.1 If the size or shape of a part is such that the part cannot be tested satisfactorily, a test may be made on a specimen machined from the stock to the dimensions given in AMS 4928 and heat treated in the same manner as the parts.

6. QUALITY: Parts shall be uniform in quality and condition, clean, sound, smooth, and free from burrs and foreign materials and from internal and external imperfections detrimental to their performance.

6.1 Parts subject to fluorescent penetrant inspection shall conform to the following standards.

6.1.1 Discontinuities transverse to grainflow, such as pipes, grinding checks, and quench cracks, shall be cause for rejection.

6.1.2 Longitudinal indications of surface seams and forming laps parallel to grainflow are acceptable within the following limits, provided the separation between indications is not less than 1/16 in. in all directions.

6.1.2.1 Sides of Head: A maximum of 3 surface indications per head is permitted and the length of each indication may be the full height of the surface. No indication shall break over either edge to a depth greater than 1/32 in. or the equivalent of the basic thread height (see Table I), whichever is less.

6.1.2.2 Top of Head and End of Stem: A maximum of 3 surface indications in each area is permitted provided the length or diameter of any individual indication does not exceed 1/32 in. or the equivalent of the basic thread height (see Table I), whichever is less.

6.1.2.3 Shank or Stem: A maximum of 5 indications is permitted. The length of any one indication may be the full length of the surface but the total length of all indications shall not exceed twice the length of the surface. No indications shall break into a fillet or over an edge.

6.1.2.4 Threads: Shall not reveal indications of cracks, seams, pipes, or rolling laps as shown by Figures 3, 4, and 5 except that indications of slight laps as shown by Figures 6, 7, and 8 will be permitted.

7. REJECTIONS: Parts not conforming to this specification or to authorized modifications will be subject to rejection.

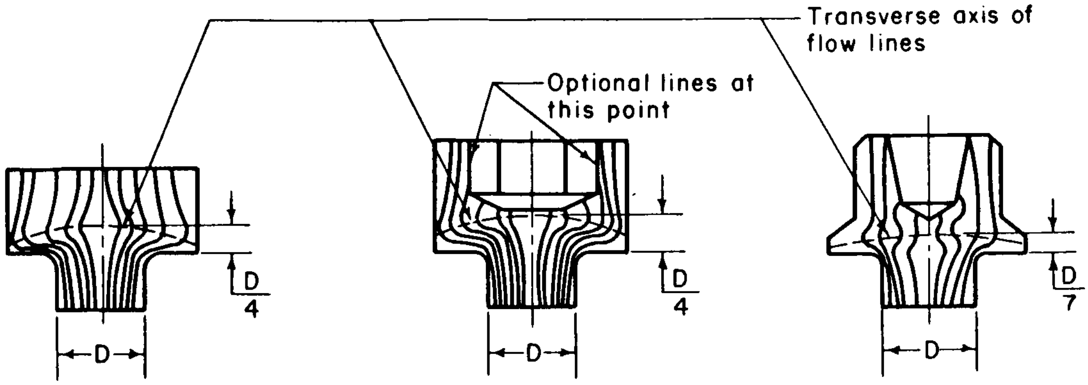


Figure 1A

Figure 1B

Figure 1C

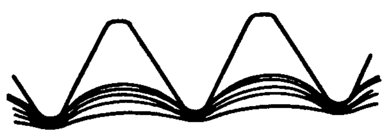


Figure 2.
Flow Lines
Rolled Thread

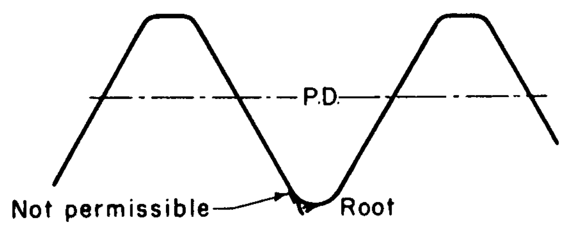


Figure 3.
Rolled Thread

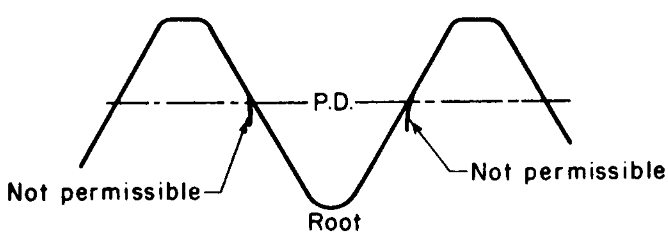
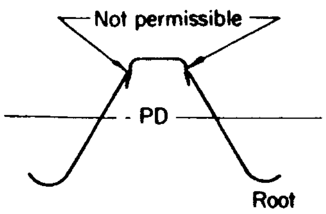
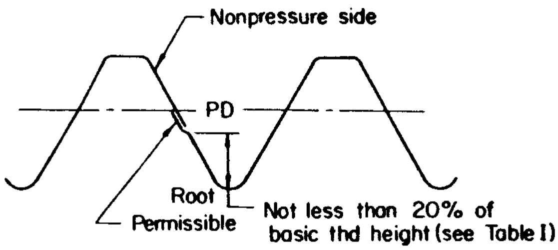


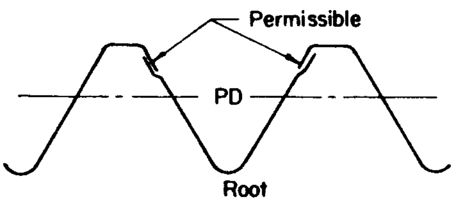
Figure 4.
Rolled Thread



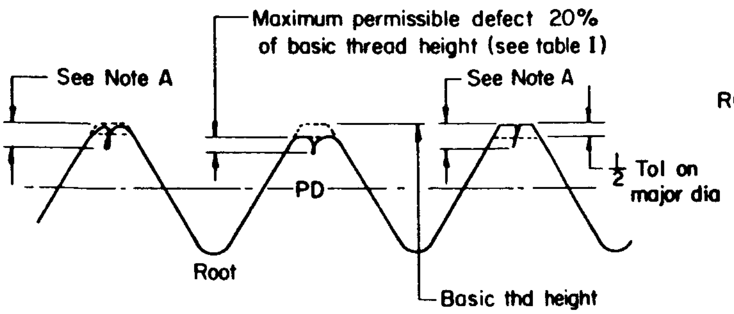
ϕ FIGURE 5.
ROLLED THREAD



ϕ FIGURE 6.
ROLLED THREAD



ϕ FIGURE 7.
ROLLED THREAD



Note A : Depth of defect equals 20% of basic thread height plus one-half the difference of the actual major diameter and minimum major diameter.

ϕ FIGURE 8.
ROLLED THREAD

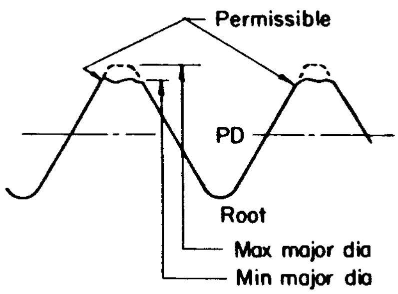


FIGURE 9.
ROLLED THREAD

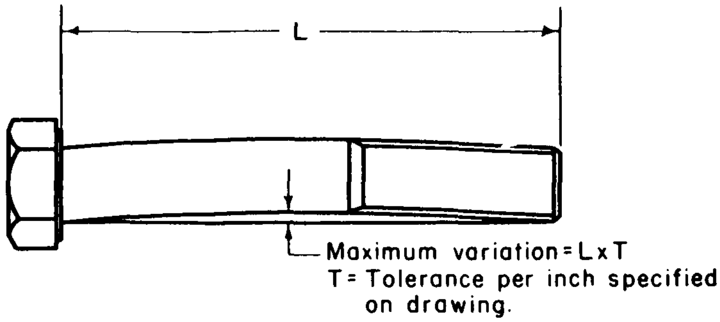


FIGURE 10.

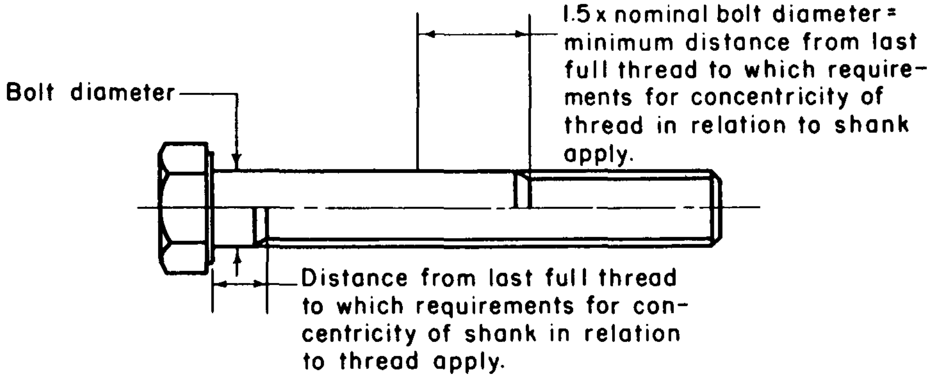


FIGURE 11.

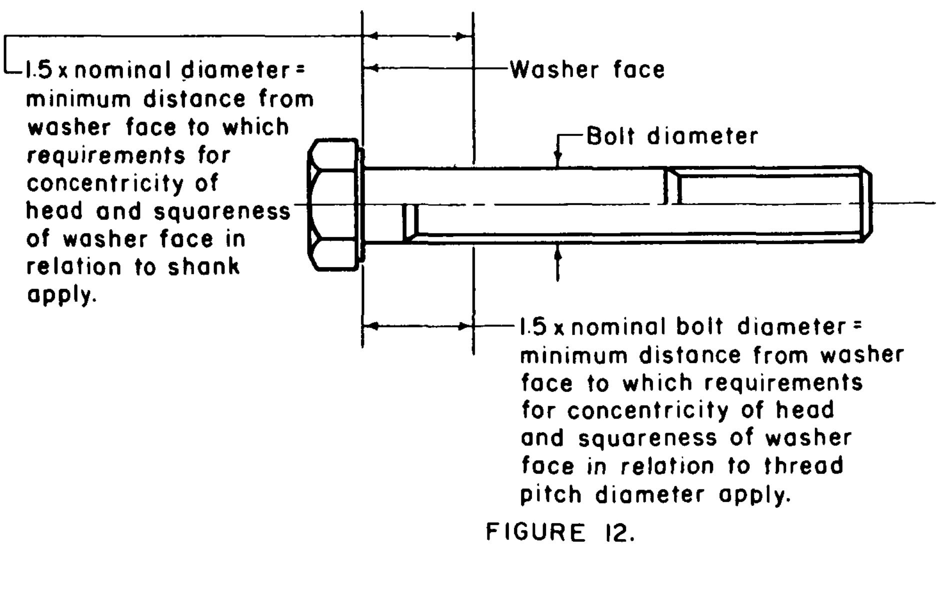


FIGURE 12.

TABLE I

AMERICAN NATIONAL AND UNIFIED THREADS

THREADS PER INCH	BASIC THD HEIGHT REF	20% BASIC THD HEIGHT
80	0.0081	0.0016
72	0.0090	0.0018
64	0.0102	0.0020
56	0.0116	0.0023
48	0.0135	0.0027
44	0.0148	0.0030
40	0.0162	0.0032
36	0.0180	0.0036
32	0.0203	0.0041
28	0.0232	0.0046
24	0.0271	0.0054
20	0.0325	0.0065
18	0.0361	0.0072
16	0.0406	0.0081
14	0.0464	0.0093
13	0.0500	0.0100
12	0.0541	0.0108
11	0.0590	0.0118
10	0.0650	0.0130
9	0.0722	0.0144
8	0.0812	0.0163

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MECHANICAL FASTENING OF TITANIUM AND ITS ALLOYS

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This document has also been reviewed and approved for technical accuracy.

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